Climatic factors contributing to long-term variations of surface fine dust concentration in the United States

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Abstract. High concentration of dust particles can cause respiratory problems and increase non-accidental mortality. Studies found fine dust (with aerodynamic diameter less than 2.5 microns) is an important component of the total PM2.5 mass in the western and central U.S. in spring and summer and has positive trends. This work examines climatic factors influencing long-term variations of surface fine dust concentration in the U.S. using station data from the Interagency Monitoring Protected Visual Environments (IMPROVE) network during 1990-2015. The variations of the fine dust concentration can be largely explained by the variations of precipitation, surface bareness, and 10 m wind speed. Moreover, including convective parameters such as convective inhibition (CIN) and convective available potential energy (CAPE) that reveal the stability of the atmosphere better explains the variations and trends over the Great Plains from spring to fall.

While the positive trend of fine dust concentration in the Southwest in spring is associated with precipitation deficit, the increase of fine dust over the central Great Plains in summer is largely associated with enhanced CIN and weakened CAPE, which are caused by increased atmospheric stability due to surface drying and lower troposphere warming. The strengthening of the Great Plains low-level jet also contributes to the increase of fine dust concentration in the central Great Plains in summer via its positive correlation with surface winds and negative correlation with CIN.

Summer dusty days in the central Great Plains are usually associated with a westward extension of the North Atlantic subtropical high that intensifies the Great Plains low-level jet and also results in a stable atmosphere with subsidence and reduced precipitation.

1. Introduction

Mineral dust is one of the most abundant atmospheric aerosols by mass. It is lifted to the atmosphere by strong wind from dry and bare surfaces. Severe dust storms have far-reaching socioeconomic impacts, affecting public transportation and health (e.g., Morman and Plumlee, 2013) by degrading visibility and causing traffic accidents, breathing problems, and lung disease. Dust storms are found to be associated with increases in non-accidental mortality in the U.S. during 1993-2005 (Crooks et al., 2016).

Major dust sources in the United States are located over the western and the central U.S. While several deserts are located over the western U.S., e.g., the Mojave, Sonoran, and northern Chihuahuan deserts, over the central U.S. the dust sources are largely anthropogenic, in association with agriculture activities (Ginoux et al., 2012). Climate models project a drying trend in the late half of the 21st century over the southwest and central U.S. (e.g., Seager et al., 2007; Cook et al., 2015), regions largely collocated with the major dust sources in the U.S. This raises questions such as how future dust activities will change in the U.S. To project future dust variations, we first need to understand how dust activity varies in the present day. Pu and Ginoux (2017) explored this question using dust optical depth (DOD) derived from MODIS Deep Blue (M-DB2) aerosol products during 2003-2015 and found that variations of dust activity in the U.S. are largely associated with precipitation, near surface wind speed, and surface bareness.

While DOD describes the total optical depth of dust aerosols with different sizes and is widely used to study climate-dust interactions, fine dust with aerodynamic diameter less than 2.5 μm is more frequently used for air quality purposes. Fine dust contributes about 40-50% of total Particulate Matter 2.5 (PM2.5) mass over the southwestern U.S. in spring and about 20-30% over the southwestern to central U.S. in summer (Hand et al., 2017).

Stations in the network of the Interagency Monitoring of Protected Visual Environments (IMPROVE) have collected near surface PM2.5 samples in the U.S. since 1988 (Malm et al., 1994; Hand et al., 2011). Analysis of chemical elements is used to derive surface fine dust concentration. Due to its long temporal coverage, this dataset has been widely used to study long-term variations of surface fine dust in the U.S. Using IMPROVE data, Hand et al. (2016) found an increasing trend of fine dust in spring in the southwestern U.S. during 1995-2014 and related this trend to a negative Pacific decadal oscillation (PDO) from 2007 to 2014. Tong et al. (2017) also found a rapid increase of dust storm activity in the Southwest from 1988 to 2011 and related the trend to sea surface temperature variations in the Pacific. Later, Hand et al. (2017) examined the trends of IMPROVE fine dust concentration in different seasons from 2000 to 2014 and found positive trends over the southwestern U.S. in spring and over the central U.S. in summer and fall. Similarly, Zhang et al. (2017) also found a positive trend of fine dust over the central U.S. from 2005 to 2015 and suggested this trend may contribute to the increase of absorbing aerosol optical depth in the region. Nonetheless, the possible causes of the fine dust trends, especially the increase of fine dust over the central U.S., have not been thoroughly discussed by previous studies. Here, we explore the underlying factors driving the long-term variations of fine dust from 1990 to 2015. We start with local environmental factors and then examine the possible influence of the low-level jet over the Great Plains on fine dust concentration in summer.

The following section describes the data and analysis method used in the paper. Section 3 presents our major results and conclusions are summarized in Section 4.

2. Data and Methodology

2.1 IMPROVE fine dust

IMPROVE stations are located in National Parks and wilderness areas in the United States, with PM2.5 sampling performed twice weekly (Wednesday and Saturday; Malm et al. 1994) prior to 2000 and every third day afterwards. Records from 204 stations within a domain of 15°-53°N and 60°-127°W are used in this study, and most of the stations have data extending back more than 10 years (Fig. S1 in the Supplement). Elemental concentration is determined from X-ray fluorescence, and fine dust concentration is calculated using the concentrations of aluminum (Al), silicon (Si), calcium (Ca), iron (Fe), and titanium (Ti) by assuming oxide norms associated with predominant soil species (Malm et al., 1994; their Eq. 5). More details regarding IMPROVE stations, sampling, and analysis method can be found in previous studies (Hand et al., 2011; 2012; 2016; 2017).

We averaged daily station data to monthly means and then interpolated them to a 0.5° by 0.5° grid using inverse distance weighted interpolation, i.e., weights depending on the inverse cubic distance between the site location and the interpolated grid point. All daily data are used to calculate monthly mean. We tried the criteria of about 50% completeness (i.e., at least 5 records in each month) for calculating monthly mean, and the results are similar. In daily composite analysis, daily station data are interpolated to a 0.5° by 0.5° grid using the same method. Least squares linear trend analysis is applied to the interpolated data, and student-t test is used for statistical significance test. We realize that the time-varying station numbers could contribute to the uncertainties of our trend analysis; so similar analysis is also applied to station data with long-term records (see Fig. 1 for details).

Following Pu and Ginoux (2017), two dusty regions are selected for analysis. The southwestern U.S. (WST for short; 32°-42°N, 105°-124°W) and Great Plains (GP for short; 25°-49°N, 95°-105°W) cover the major dust source regions in the U.S. (black boxes in Fig. 1). In later analyses, we also focus on the central Great Plains (CGP for short; 32°-40°N, 95°-102°W) in summer to examine the positive trend of fine dust in the region.

2.2 Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) products

CALIOP is the two-wavelength polarization lidar carried by Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, which was launched in April 2006 (Winker et al., 2004; 2007). CALIOP measures backscattered radiances attenuated by the presence of aerosols and clouds, whose microphysical and optical properties are retrieved. Daily products are available since June 2006. To examine the vertical profile of dust concentration in the U.S., both the daily 532 nm total attenuated backscatter from Level 1 product and the depolarization ratio from Level 2 product are used. The depolarization ratio can be used to separate spherical and non-spherical hydrometeors and aerosols (Sassen, 1991), and here a threshold of 0.2 is used to separate non-spherical dust from other aerosols (Li et al., 2010).

2.2 Precipitation

The Precipitation Reconstruction over Land (PRECL; Chen et al., 2002) from the National Oceanic and Atmospheric Administration (NOAA) is a global analysis available monthly from 1948 to present at a 1° by 1° resolution. Its relative high-resolution and long records are suitable to study long-term connections between fine dust and precipitation. The dataset is derived from gauge observations from the Global Historical Climatology Network (GHCN), version 2, and the Climate Anomaly Monitoring System (CAMS) datasets. Monthly precipitation from 1990 to 2015 is used.

2.3 Leaf area index (LAI)

Monthly LAI derived from the version 4 of Climate Data Record (CDR) of Advanced Very High Resolution Radiometer (AVHRR) surface reflectance (Claverie et al., 2014) and produced by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the University of Maryland is used. The gridded monthly data are on a 0.05° by 0.05° horizontal resolution and available from 1981 to present. A detailed discussion on the algorithm and evaluation of the dataset can be found by Claverie et al. (2016). This dataset is selected due to its high spatial resolution and long temporal coverage. Monthly data from 1990 to 2015 are used.

Surface bareness is derived from seasonal mean LAI, and is calculated following Pu and Ginoux (2017),

$$Bareness = exp(-1 \times LAI) \quad . \qquad (1)$$

2.4 Reanalysis

North American Regional Reanalysis (NARR; Mesinger et al., 2006) provides 3-hourly, daily, and monthly meteorological variables from 1979 to the present at a high spatial resolution (i.e., about 32km horizontally). Precipitation in the NARR is assimilated with observations. Here daily precipitation is used for daily composite analysis in section 3.3.2. The reanalysis reasonably captures the hydroclimatic fields in the continental U.S. on multiple time scales (Ruiz-Barradas and Nigam, 2006; Ruane, 2010a, b), thus is suitable to study the connection between fine dust concentration and local hydroclimatic variables. Daily and monthly convective variables such as convective inhibition (CIN), and convective available potential energy (CAPE) are used. CIN is defined as the energy that a parcel needs to overcome to rise above the level of free convection (LFC), and is usually written as:

$$CIN = -\int_{P_{sfc}}^{P_{LFC}} R_d\left(T_{vp} - T_{ve}\right) dlnp \quad , \quad (2)$$

where P_{LFC} is the pressure at LFC, P_{sfc} is the pressure at the surface, R_d is the specific gas constant for dry air, T_{vp} is the virtual temperature of the lifted parcel, and T_{ve} is the virtual temperature of the environment. CIN is usually a negative variable, with bigger CIN (in absolute value) indicating greater inhibition. On the other hand, CAPE describes the positive buoyancy of an air particle from the LFC to the equilibrium level (neutral buoyancy), and can be written as:

$$CAPE = -\int_{P_{LFC}}^{P_{EL}} R_d\left(T_{vp} - T_{ve}\right) dlnp \quad , \quad (3)$$

where P_{EL} is the pressure at the equilibrium level. Both CIN and CAPE describe the stability of the atmosphere, and usually convection easily occurs when CAPE is high and CIN is low (in absolute value; e.g., Colby, 1984; Riemann-Campe et al., 2009; Myoung and Nielsen-Gammon, 2010a). Note the two variables can sometimes vary in opposite directions. Indeed, when CAPE is high, strong inhibition may still prohibit the occurrence of deep convection.

In addition, daily and monthly means of horizontal wind speed at 900 hPa, temperature at 700 hPa (T_{700}), 10 m wind speed, dew point temperature (T_{dp}), and 2 m air temperature (T_{2m}), total cloud cover, total and convective precipitation are used.

Another reanalysis used in this work is the ERA-Interim (Dee et al., 2011) from the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim is a global reanalysis with a horizontal resolution of T255 (about 0.7° or 80 km) and 37 vertical levels, available from 1979 to present. It complements the regional reanalysis by providing a larger domain to analyze circulation variations and also a few surface variables (such as surface turbulent stress) that are not available in the NARR. 6-hourly analysis and 3-hourly forecast variables such as surface turbulent stress, vertical and horizontal winds, air temperature, and specific humidity from 1000 to 200 hPa, 850 hPa winds and geopotential height are used to calculate daily means of these variables.

2.5 Multiple-linear regression

To understand the connection between the potentially controlling factors and the variation of fine dust concentration, multiple-linear regressions are applied by regressing the observed gridded fine dust concentration onto 3, 4, or 5 standardized controlling factors, a method similar to the one used by Pu and Ginoux (2017). Since multiple controlling factors and gridded surface fine dust have different horizontal resolutions, for the regression analysis we first interpolated all variables to a 1° by 1° grid, then apply the regression at each grid point.

The fine dust concentration can be reconstructed by using the regression coefficients and observed variations of the controlling factors (such as precipitation, surface wind, and bareness). We focus our analysis on two statistical properties: correlations of regional averaged time series and (centered) pattern correlations (e.g., Pu et al., 2016b) for the trends. These two properties are calculated for both observed and regression model estimated (i.e., reconstructed) fine dust concentrations.

3. Results

3.1 Trends of surface fine dust concentration during 1990-2015 and local controlling factors

Figure 1 shows the trend of fine dust concentration from gridded data (shading) and also those from stations with at least 23 years of consecutive records (colored circles) from 1990 to 2015. Most long-term sites show trends similar to those from the interpolated data, with a few exceptions, e.g., over northern Alabama, where interpolated data show positive trends due to the influence of nearby stations with shorter records (Fig. S1 in the Supplement). Significant positive trends are found over the southwestern U.S. in spring (MAM), over the central to southern Great Plains in summer (JJA), and the northern Great Plains in fall (SON). Dust concentration also increases over southwestern Arizona (up to 0.06 μg m^{-3} yr^{-1}), by about 2.5% of its climatological value (Fig. S2 in the Supplement) per year, in all seasons. A similar increasing trend of fine dust in southern Arizona in spring from 1988 to 2009 is also noticed by Sorooshian et al. (2011). A decreasing trend is found over the northeastern U.S. in all seasons as well. The overall pattern is somewhat similar to the trend identified by Hand et al. (2017; their Fig. 9) for 2000-2014, who also found increasing trends of fine dust in the Southwest in spring and over the CGP in summer. One thing we want to point out here is that most of the stations in the Great Plains have records shorter than 15 years, with only three stations having records for more than 25 years (Fig. S1 in the Supplement), therefore the positive trends here are combinations of interpolated information from nearby stations in the early period (before ~2002) and more reliable data largely from local stations in the late period.

As suggested by previous studies, the trend of fine dust may be biased due to suspicious trends in some chemical species (Al, Si, and Ti) used to construct fine dust in association with changes of analytical methods (e.g., Hyslop et al., 2015; Hand et al., 2016; Hand et al., 2017). Fe has been suggested as a good proxy of fine dust since it's more stable and is a key component of dust (Hand et al. 2016; 2017). We examined the trend of fine Fe (Fig. S3 in the Supplement), and found the pattern is very similar to the trend of fine dust. In fact, we found the correlations between seasonal mean fine dust and Fe (both gridded data and long-term stations) are around 0.90 (significant at the 99% confidence level) in most part of the U.S. during 1990-2015 (Fig. S4 in the Supplement). This suggests the trends revealed directly from surface fine dust record are comparably reliable as those calculated from Fe. So we use fine dust concentration for this analysis.

What are the dominant factors influencing the variations of surface fine dust concentration? Hand et al. (2016) found that the PDO played an important role in the variability of fine dust concentration over the Southwest in March by creating a windier, drier, and less vegetated environment. We would like to extend their analysis to other seasons and regions. In addition, we focus on identifying key controlling factors at the local level because remote forcings such as the PDO influence dust variations through their tele-connection with local controlling factors. Pu and Ginoux (2017) found that local precipitation, surface bareness, and surface wind speed could explain 49% to 88% of the variances of dust event frequency (derived from DOD) over the western U.S. and the Great Plains in different seasons from 2003 to 2015. We first examine to what extent these factors can explain the variance of near surface fine dust concentration. Similar to Pu and Ginoux (2017), we do not separate the contribution from local emissions or remote transport to the fine dust concentration, although contributions from Asian dust in spring over the western U.S. (Fischer et al., 2009; Creamean et al., 2014; Yu et al., 2012) and from North African dust in summer over the southeastern U.S. (Perry et al., 1997; Prospero, 1999a) have been observed.

Figures 2a-d show the dominant controlling factor among precipitation, surface wind, and bareness for fine dust concentration variations on the interannual time scale from 1990-2015 at each grid point. Precipitation plays an important role in most parts of the southern U.S. in winter. In spring, surface wind starts to dominate the variations of fine dust along the Gulf coast and eastern Great Plains, consistent with the intensification of the Great Plains low-level jet (e.g., Helfand and Schubert, 1995; Weaver and Nigam, 2008; Pu and Dickinson, 2014; Pu et al., 2016a) in April and May, while bareness is important over the western Great Plains and the Midwest. During summer, the influence of surface wind speed gets stronger, especially over western Arizona and the lower Mississippi basin, whereas bareness and precipitation are also important in many parts of the Great Plains and western U.S. Precipitation becomes the dominant factor over most parts of the U.S. again in fall, with surface winds playing a weak role over the southeast and northeast coasts.

The regression coefficients obtained here share some similarity with those shown by Pu and Ginoux, (2017; their Fig 4) using DOD, e.g., the importance of surface bareness in the Great Plains in spring and summer. However, there are also quite large differences, likely due to different periods of regression and the fact that the DOD and surface fine dust concentration are not always linearly related to each other (Fig. S5 in the Supplement). Fine dust covers a small fraction of the total mass distribution of dust particles, thus the connections between fine dust concentration and the controlling factors could be different from those with the DOD. For example, the scavenging effect of precipitation is more efficient on small particles (e.g., Zender et al., 2003) and as a result precipitation generally plays an overall more important role on fine dust variations than on the DOD, especially in winter, spring, and fall.

The correlations of regional averaged time series between reconstructed fine dust concentration in the southwestern U.S. (using regression coefficients and observed variations of precipitation, surface wind, and bareness) and that from the IMPROVE range from 0.69 in fall to 0.82 in winter, indicating that the above three factors explain about 48% to 67% variances of fine dust in the Southwest from 1990 to 2015. Over the Great Plains, these factors only explain 32% to 48% variances statistically, much lower than over the Southwest. Also note the low confidence level of the regression coefficients over the CGP in summer (Fig. 2c), which indicates that the above three factors are not sufficient to well explain the variations of fine dust in the Great Plains.

The development of dust storms has long been related to convection and atmospheric stability (e.g., Marsham et al., 2008; Cuesta et al., 2009). Here we examine whether the variances of fine dust concentration and trend can be better represented by adding CIN (i.e., four-factor) and both CIN and CAPE (i.e., five-factor) in addition to the three factors (i.e., three-factor) discussed above.

Figure 2e shows correlations (blue bars) between the observed and the reconstructed regional mean fine dust concentration using three-, four-, and five-factor regressions, and corresponding pattern correlations (pink dots) between trends from the observed and reconstructed fine dust for the Great Plains and the southwestern U.S. Over the Great Plains, pattern correlations are largely improved when including CIN and CAPE, especially in spring (from 0.30 to 0.89) and summer (from 0.34 to 0.93), although slightly decrease in winter. The correlations of regional mean time series between the reconstructed and observed fine dust are also slightly improved from three-factor regression to five-factor regression. Over the Southwest, the improvement of pattern correlation is smaller, and the correlations of time series change little when including CIN and CAPE.

The collinearity among the factors used in the multiple linear regression can be examined by the variance inflation factor (VIF; O'Brien, 2007; Abudu et al., 2011), and usually values between 5 and 10 are considered high collinearity and the results of regression are less reliable. Increasing the number of predictors in multiple linear regression generally increase VIFs. The VIFs for three-factor regression are around 1 and 2 in most areas, with a few spots around 3 (not shown), while the VIFs for five-factor regression are slightly higher, especially for CIN and CAPE over the Southwest (Figs. S6 and 7 in the Supplement). The increase of VIF and relatively weak improvement in the correlations in the Southwest when adding the convective factors suggest that three factors (precipitation, surface wind, and bareness) are sufficient to capture the variations and trend of surface fine dust in the region. Over the Great Plains, adding CIN and CAPE can better explain the variations.

We now examine key factors driving the observed positive trends of fine dust concentration in spring and summer, the dustiest seasons (Fig. S2 in the Supplement), based on the above analysis. Specifically, we focus on the positive trends of surface fine dust over the southwestern U.S. in spring and over the CGP in summer (Fig. 1b and c). Figure 3a shows the trend of observed and reconstructed fine dust concentrations in spring along with three components contributed to the reconstructed trend (i.e., from precipitation, bareness, and surface wind). The reconstructed trend (Reg (all)) largely captures the positive trend in the Southwest shown in the observation (Obs). Among the three factors, precipitation plays the most important role in contributing to the positive trend over the Southwest, consistent with its dominant role in explaining observed interannual variability (Fig. 2b). The increase of fine dust is mainly associated with a decreasing trend of precipitation in the Southwest (Fig. 3b). Such a drying trend has been related to an increase of anticyclonic conditions in the North East Pacific (Prein et al., 2016) and an intensification of Pacific trades during 2002-2012 (Delworth et al., 2015).

The reconstructed summer trend using coefficients from five-factor regression is very similar to the observation, with a pattern correlation of 0.95 in the domain (Fig. 4a). The positive trend over the CGP is largely contributed by CIN, with a positive center at northern Texas, western Kansas, and Oklahoma. Parts of the positive trend over

Oklahoma and western Kansas are contributed by CAPE. In fact, both CIN and CAPE have significant negative trends over the CGP, although the trend of CAPE is slightly weaker than that of CIN (Fig. 4b). A decrease of CIN (i.e., an increase in its absolute value) denotes an increasing inhibition of convection, while weakened CAPE denotes a decreasing instability associated with moist convection. Note that CIN is also significantly negatively correlated with fine dust concentration on interannual time scale (r= -0.39, p= 0.05). This again indicates that CIN plays a more important role than CAPE in the recent positive trend of fine dust.

Both the trends of the CIN and CAPE denote an increase of atmospheric stability. Changes of CIN and CAPE have been related to boundary layer or near-surface temperature and moisture (e.g., Ye et al., 1998; Gettelman et al., 2002; Alappattu and Kunhikrishnan, 2009). Myoung and Nielsen-Gammon (2010b) found that the variations of CIN over Texas in the warm season can be well represented by the differences of temperature at 700 hPa (T_{700}) and surface dew point temperature (T_{dp}), i.e., T_{700}-T_{dp}. While T_{700} is a good proxy for temperature at the free-troposphere below the LFC, T_{dp} denotes the dryness at the surface. Thus, T_{700}-T_{dp} represents a joint effect of surface drying and warming at 700 hPa, a positive anomaly of which indicates increased atmospheric stability. Here we find both CIN and CAPE have significant negative correlations with T_{700}-T_{dp} over the CGP (Fig. 4c). A significant positive trend of T_{700}-T_{dp} is also found, supporting the assumption that the atmospheric stability is enhanced during the period. Such a changes of stability is largely due to the increase of T_{700}, although surface drying also contributes.

CIN is also found to be significantly correlated with rain days (daily precipitation ≥ 1 mm day^{-1}) in summer in Texas (Myoung and Nielsen-Gammon, 2010b). Here a similar positive correlation between CIN and rain days in the CGP is also found from 1990 to 2015 ($r=0.79$, $p<0.001$), suggesting that CIN could influence fine dust concentration via its connection with rain days. A stable atmosphere prevents deep moist convection, which reduces the chance of scavenging by precipitation, and also likely prevents dilution of fine dust concentration in the boundary layer with the clean air above through convective mixing. The connection underlying CIN and fine dust concentration is further discussed in section 3.3 using daily data.

3.2 The connection between the Great Plains low-level jet and summertime fine dust variations in the CGP

An important feature related to the moisture and heat transport and precipitation in the Great Plains from late spring to summer is the Great Plains low-level jet, which develops in April and reaches its maximum wind speed in June and July at around 900 hPa (e.g., Weaver and Nigam, 2008; Pu et al., 2016a). The southerly jet covers most of the southern to central Great Plains, and turns into a westerly around 40° N passing through the Midwest. How this jet may influence the dust concentration in the CGP in summer is examined here.

Figure 5a shows the time series of the jet index in summer following the definition of Weaver and Nigam (2008) by averaging 900 hPa meridional wind speed at the jet core (25°-35°N, 97°-102°W) from 1990 to 2015. The jet index is significantly positively correlated with fine dust concentration in the CGP in summer ($r= 0.56$, $p<0.01$)

and also has a significant positive trend, suggesting that the jet also contributes to the increasing of fine dust in the CGP. Such a positive connection between the jet and fine dust concentration can be explained by jet's negative correlation with CIN and positive correlation with the near surface wind speed in the CGP (Figs. 5b). An intensified jet increases the near surface wind speed and meanwhile increases the stability of atmosphere over the CGP by advecting moisture away to the Midwest.

Because most of the IMPROVE sites (4 out of 6) in the CGP only have records since 2002, correlations between the jet index and fine dust concentration, CIN, and surface wind for 2002-2015 are also calculated (Fig. 5c). The patterns are similar to those during 1990-2015.

Dust from Africa can be transported to the southeastern U.S. and even Texas in summer (e.g., Perry et al., 1997; Prospero, 1999b, a; 2010; 2014; Bozlaker et al., 2013). Can the intensified jet transport more African dust and thus contribute to the increase of fine dust in the CGP? Fully addressing this question will require a dust model that can well reproduce the emission and transport processes of African dust, which is beyond the scope of this paper. Here we discuss this question based on observational analysis. The regression and trend analysis above suggests that local atmospheric stability largely contributes to the positive trend. Since African dust is transported to the continental U.S. passing through the Caribbean Sea and the Gulf of Mexico, we assume that the variations of fine dust in stations nearby would reveal the influence of African dust. Two of such stations, VIIS1 (18.3°N, 64.8°W) in the Virgin Islands National Park and EVER1 (25.4°N, 80.7°W) in the Everglades National Park, are used. It is found that the records from these stations have significantly positive correlations with fine dust concentration over the southeastern U.S. in JJA, but not over the CGP (Fig. S8 in the Supplement). This suggests that the influence of African dust is largely over the Southeast on seasonal mean, consistent with the results of Hand et al. (2017), who found the influence of North African dust are mainly over the Southeast, Appalachia, and Virgin islands regions in summer as indicated by a shift of elemental composition in IMPROVE sites.

3.3 Factors contributing to high dust concentration over the CGP in summer

While the negative correlation between fine dust concentration and precipitation in the Southwest is straightforward, the correlation between fine dust and CIN in the CGP is less obvious. Here we further examine the connection between fine dust and CIN and other factors associated with high dust concentration in the area using daily events. As mentioned earlier, since most stations in the CGP have records since 2002, the following analysis focuses on summer during 2002-2015.

3.3.1 Connection between surface fine dust concentration and CIN

What's the physical connection between CIN and surface fine dust concentration? Here we first explore the connection between CIN and a variable that is closely related to dust emission. Figures 6a-c show the scatter plot of standardized (means are removed and then divided by one standard deviation) CIN and friction velocity (U^*) anomalies, for all the days in summer from 2002 to 2015, days when IMPROVE records are available (431 days), and dusty days, defined as days when daily anomaly of IMPROVE observation is greater than one standard deviation (52 days), respectively. U^* is defined as the following,

$$U^* = ([\tau/\rho])^{1/2} = [(\overline{u'w'})^2 + (\overline{v'w'})^2]^{1/4} \ , \qquad (4)$$

where τ is the Reynolds stress and ρ is air density, and $\overline{u'w'}$ and $\overline{v'w'}$ are vertical flux of horizontal momentum. We calculated U^* using components of surface turbulent stress ($-\rho\overline{u'w'}$, $-\rho\overline{v'w'}$) from the ERA-Interim. U^* has long been related to dust emission (e.g., Gillette and Passi, 1988; Marticorena and Bergametti, 1995; Zender et al., 2003). As shown in Figs. 6a-c, CIN is significantly negatively related to U^* in all summer days and dusty days. This indicates a large negative CIN, or great inhibition for convection, is related to stronger near surface turbulent fluxes and U^*. How does CIN influence U^*?

In the CGP, both CIN and U^* are significantly correlated with near surface temperature, T_{2m}, in JJA and for days when fine dust records are available (Table 1), indicating that CIN is connected with U^* via their mutual connection with near surface temperature. Note such a connection seems not valid during dusty days (correlation between T_{2m} and U^* is not significant). Similarly, we found significant correlations between CIN and T_{700}-T_{dp}, and between T_{700}-T_{dp} and U^* (Table 1). This again, suggests that CIN is connected with U^* via its connection with surface variables such as temperature and dryness. Variables in Table 1 are all from the ERA-Interim (except CIN) to be consistent with U^*. Results are similar if using NARR variables.

One hypothesis for the connection between CIN and U^* on dusty days is shown in Table 2. A significant positive correlation between CIN and vertical wind at 850 hPa (w850) is found, indicating that when the inhibition is strong, it favors subsidence. This is consistent with the finding by Riemann-Campe et al. (2009) who found in climatology high CIN value is located over subtropical regions with strong subsidence. The subsidence may transport momentum downward and promote U^*. This is consistent with the negative correlation between U^* and w850 (Table 2). However, we also notice that the above connections on dusty days are not valid if using w850 from the NARR, suggesting further investigation on this mechanism is needed.

In addition to the connection between CIN and surface variables, the possible mechanism that strong inhibition prevents dilution is also examined. We found four examples in CALIOP snapshots over the CGP when the daily anomaly of near surface fine dust concentration from the IMPROVE network is greater than one standard deviation. Figure 7 shows nighttime 532 nm total attenuated backscatter (shading) on August 10th, 2007 (top) and on June 21st, 2013 (bottom). Black contours show area with depolarization ratio ≥ 0.2, denoting dust aerosols. In both cases, the inhibition is quite strong, with daily CIN anomaly greater than one standard deviation. The difference between the two cases is that on June 21st, 2013, CAPE is higher, which leads to some convection as denoted by the clouds above. However, in both cases, with strong inhibition, dust particles are largely located in a layer between the surface and 2 km. Figure 8 shows a different situation when CIN has positive anomaly (i.e., weak inhibition). In these cases, dust particle extends up to 4 km, and surface fine dust concentrations in the CGP (with anomalies of 2.3 and 2.1 μg m^{-3}) are also lower than those in Fig. 7 (with anomalies of 4.0 and 7.1 μg m^{-3}). Nonetheless, more cases are needed to further verify this mechanism. The anomalous high fine dust concentration in Everglades National Park (Figs. 7-8) in three of the four cases shown here suggest that there may be a contribution from African dust in these days, but further analysis are needed to clarify the magnitude of its contribution.

3.3.2 Large-scale circulation pattern on dusty days

Figure 9 shows the daily composites of related meteorological variables on dusty days, i.e., when daily anomaly of CGP fine dust concentration is greater than one standard deviation. Anomalous high fine dust concentration is associated with a reduced CIN (Fig. 9b) in the CGP, but not so much with CAPE (Fig. 9c). CAPE is anomalously enhanced over the northern Plains and the Midwest. Both the Great Plains low-level jet, near surface wind, and friction velocity are enhanced (Figs. 9d-f). Precipitation (mostly convective precipitation) in the CGP also decreases with reduced cloud cover, but increases in the north (Figs. 9g-i), consistent with enhanced CAPE there. These features are quite consistent with our analysis above on the favorable condition of enhanced fine dust in the CGP.

Figure 10 shows the composites of vertical velocity (shading), vertical and meridional wind vectors, specific humidity (purple contours), and potential temperature (grey contours) zonally averaged over the CGP (95° -102° W), along with fine dust concentration (orange line). Anomalous dry subsidence is centered at 30°-36°N, with anomalous southerly winds at low-level associated with an intensified jet, while a rising motion of moist air is located around 38-42°N with a maximum at 700-400 hPa. The dipole pattern of anomalous vertical velocity is consistent with the precipitation anomaly in the area (Figs. 9g-h). The anomalous potential temperature contour is quite uniform near the surface at 30°-36°N with an inversion around 700 hPa, indicating a well-mixed boundary layer in the region with increased fine dust.

What causes the changes of atmospheric stability, precipitation, and winds? Figure 11 shows the composites of T_{2m} and geopotential height and winds at 850 hPa during dusty days. Following Li et al. (2012a), 1560 gpm contour is used here to denote the western edge of the North Atlantic subtropical high in the 2002-2015 climatology (blue) and on dusty days (red). A westward extension of the subtropical high during dust days is quite evident, with enhanced geopotential height over the southeastern U.S. and the Gulf of Mexico (Fig. 11b). Such a westward extension of the subtropical high intensifies the low-level jet by increasing the zonal pressure gradient, and also contributes to the anomalous precipitation and vertical velocity patterns, as similar patterns are found in previous studies associated with a westward extension of the subtropical high (e.g., Li et al., 2012a; their Figs. 3a and 4a). The formation of the North Atlantic subtropical high has been related to the land-sea heating contrast (Wu and Liu, 2003; Liu et al., 2004; Miyasaka and Nakamura, 2005; Li et al., 2012a; Li et al., 2012b). One possible reason of the westward extension of the subtropical high is the anomalous surface warming over large part of the central and eastern U.S. (Fig. 11a) on dusty days that enhances the land-sea temperature gradient.

4. Conclusions

Fine dust is an important component in the total PM 2.5 mass in the western to central U.S. in spring and summer (Hand et al. 2017). Previous studies found positive trends of fine dust concentration in the southwestern U.S. in spring and the central U.S. in summer in the past 20 years (Hand et al., 2016; 2017; Zhang et al., 2017), but the underlying causes are not clear, especially for the positive trend over the central U.S. This study examined local controlling factors associated with variations of near surface fine dust concentration from Interagency Monitoring of Protected Visual Environments

(IMPROVE) stations for 1990-2015. While precipitation, surface bareness, and surface wind speed largely control the variation of fine dust concentration in the southwestern U.S., including two convective parameters that reveal the stability of the atmosphere, convective inhibition (CIN) and convective available potential energy (CAPE), better explains the variations over the Great Plains from spring to fall.

In particular, we found that the increasing trend of fine dust concentration over the Southwest in spring is associated with a significantly decreasing trend of precipitation, while the positive trend of fine dust over the central Great Plains (CGP) is largely due to enhanced atmospheric stability revealed by enhanced CIN (greater inhibition) and decreased CAPE. Such a stability change is associated with surface drying and warming in the lower troposphere around 700 hPa, i.e., a positive trend of T_{700}-T_{dp}. A stable atmosphere prevents moist convection that can remove fine dust by in-cloud or precipitation scavenging and also likely prevents the dilution of fine dust concentration by prohibiting convective mixing between the dusty boundary layer air and the clean air above.

The variations of the fine dust concentration in the CGP are also significantly correlated to the Great Plains low-level jet, with a stronger jet corresponding to higher fine dust concentration. Such a connection is largely due to jet's positive correlation with surface wind speed and negative correlation with CIN.

The influence of CIN on dust emission in the CGP is examined using daily data in summer. It is found that CIN is significantly negatively related to surface friction velocity (U^*), i.e., with greater inhibition in association with stronger U^*. Such a connection is largely due to CIN's connection with surface variables such as 2m temperature and dew point temperature. During dusty days, another possible connection is that the anomalous subsidence associated with strong inhibition may transport momentum downward and increase surface U^*.

Dusty days in the CGP in summer are associated with a westward extension of the North Atlantic subtropical high that intensifies the Great Plains low-level jet and surface wind speed, increases atmospheric stability, and also creates anomalous subsidence over the southern to central Great Plains and reduces precipitation. The westward extension of the subtropical high is likely associated with the anomalous surface warming over the central to eastern U.S.

Our findings have important implications for future projections of fine dust variation in the U.S. Climate models have projected drying trends over the southwestern and the central U.S. (e.g., Seager et al., 2007; Cook et al., 2015) as well as an intensification of the North Atlantic subtropical high (Li et al., 2012b) in the late 21st century, all favorable to an increase of fine dust in the Southwest and CGP. Whether current increasing trends of fine dust will persist into the future requires further investigations that include factors not discussed here such as changes of anthropogenic land use, local synoptic-scale systems (e.g., cyclones and fronts), and remote forcings.

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Table 1 Correlations between friction velocity (U^*) and CIN, CIN and 2 m temperature (T_{2m}), T_{2m} and U^*, T_{700}-T_{dp} (the differences between air temperature at 700 hPa and 2m dew point temperature) and CIN, T_{700}-T_{dp} and U^* for all days in JJA from 2002 to 2015 (1288 days), days when fine dust concentration is available (431 days), and dusty days (52 days). All values are significant at the 95% confidence level (t-test) except those listed in italic.

Table 2 Correlations between U^* and CIN, CIN and vertical wind speed at 850 hPa (w850), w850 and U^* during dusty days in JJA from 2002 to 2015. All values are significant at the 95% confidence level except the value significant at the 90% confidence level is labeled with a "+" (t-test).

Figure 1. Trend (shading) of fine dust concentration (μg m^{-3}) from 1990 to 2015 in (a) DJF, (b) MAM, (c) JJA, and (d) SON from IMPROVE gridded data. Dotted areas are significant at the 95% confidence level. The colored circles show the trend at IMPROVE stations with consecutive records for at least 23 years during 1990-2015. Circles with green outlines denote that the trend is significant at the 90% confidence level. Black boxes denote the averaging areas of the southwestern U.S. (solid) and the Great Plains (dashed).

Figure 2. (a)-(d) Multiple linear regression coefficients calculated by regressing fine dust concentration from 1990-2015 onto standardized precipitation (purple), bareness (orange), and surface wind (green). Color denotes the most influential factor at each grid (i.e., the largest regression coefficient in absolute value among the three), while saturation of the color shows the magnitude of the coefficient (0 to 0.3). Areas significant at the 95% confidence levels are dotted. (e) Bar-plot showing the correlations between observed regional mean fine dust concentration and the reconstructed concentration using 3, 4, and 5 controlling factors (light, median, and deep blue), and pattern correlation between trends from the observation and from reconstructed fine dust using 3, 4, and 5 factors (light, medium, and deep pink) in the Great Plains (GP) and the southwestern U.S. (WST, black boxes in a-d). "3-factor" denotes precipitation, bareness, and surface wind, "4-factor" denotes precipitation, bareness, surface wind, and CIN, "5-factor" denotes precipitation, bareness, surface wind, CIN, and CAPE. Black boxes denote the averaging areas of the WST (solid) and GP (dashed).

Figure 3. (a) Observed (Obs) and reconstructed (Reg) trends of fine dust concentration (μg m^{-3}) using three factors in spring from 1990 to 2015. The contributions from each factor (precipitation, bareness, and surface wind) to the overall reconstructed trend are also shown (second row). Dotted areas are significant at the 90% confidence level. Pattern correlation between reconstructed dust concentration trends and observed trends in the domain (25°-49.5°N, 66.5°-125°W) are shown at the top right corner of each plot. Black box denotes the southwestern U.S. (WST). (b) Time series of fine dust concentration (cyan) and precipitation (purple) averaged over the WST and their linear trends (dashed lines; values are listed at bottom left) in spring from 1990 to 2015. Gray shading denotes ±one standard error of the observations. The correlation between fine dust and precipitation is also listed at the bottom in purple.

Figure 4. (a) Observed (Obs) and reconstructed (Reg) tends of fine dust concentration (μg m^{-3}) using five factors in summer from 1990-2015. The contributions from each factor (precipitation, bareness, surface wind, CAPE, and CIN) are also shown (second and third rows). Dotted areas are significant at the 90% confidence level. Pattern correlation between reconstructed dust concentration trends and the observed trends in the domain (25°-49.5°N, 66.5°-125°W) are shown at the right corner of each plot. Black box denotes the central Great Plains (CGP). (b) Time series of fine dust concentration (cyan), CIN (orange), and CAPE (deep blue) averaged over the CGP and their linear trends (dashed lines) in summer from 1990-2015. Gray shading denotes ±one standard error of the observations. (c) Time series of T_{700}-T_{dp} (black), T_{700} (green) and T_{dp} (light blue) and their linear trends (dashed lines) in summer from 1990 to 2015.

Figure 5. (a) Time series of fine dust concentration (μg m^{-3}) averaged in the CGP (cyan) and the index of the Great Plains low-level jet (magenta) and their trends (dashed line) in JJA from 1990 to 2015. Gray shading denotes ±one standard error of the observations. Correlations between the jet index and fine dust concentration, CIN, and near surface wind speed for (b) 1990-2015 and (c) 2002-2015. Colored circles denotes correlations at IMPROVE stations, with green outlines denotes the correlation is significant at the 90% confidence level. Areas significant at the 95% confidence level are dotted in (b) and significant at the 90% confidence level are dotted in (c). Black box in (b)-(c) denotes the CGP region, and deep pink box denotes the averaging area for the jet index.

Figure 6. Scatter plot of standardized friction velocity (U^*) and CIN anomalies for (a) all days in JJA from 2002-2015, (b) days when fine dust data are available, and (c) dusty days (when daily fine dust concentration anomaly is greater than one standard deviation).

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Figure 8. Same as Fig. 7 but for July 2nd, 2011 (top) and July 2nd, 2012 (bottom). Only positive CIN anomalies from 25 to 50 J kg^{-1} are shown (light purple contour).

Figure 9. Daily composites of the anomalies of (a) fine dust concentration (μg m^{-3}), (b) CIN (J kg^{-1}), (c) CAPE (J kg^{-1}), (d) 900 hPa wind speed (m s^{-1}), (e) 10 m wind speed (m s^{-1}), (f) U^* (m s^{-1}), (g) total precipitation (mm day^{-1}), (h) convective precipitation (mm day^{-1}), and (i) total cloud cover (%) during dusty days in JJA from 2002 to 2015. Dotted areas are significant at the 95% confidence level. 900 hPa and 10 m wind anomalies (green vectors) significant at the 95% confidence level are shown in (d) and (e), respectively. Black boxes denote the CGP region.

Figure 10. Daily composite of the anomalies of vertical velocity (shading; 10^{-2} m s^{-1}), potential temperature (grey contours; K), and specific humidity (purple contours; g kg^{-1}) from the ERA-Interim, and fine dust concentration anomalies (bottom; orange line) averaged between 95° and 102° W for dusty days in JJA from 2002 to 2015. Dotted area denotes vertical velocity significant at the 90% confidence level. Topography is masked out in grey. Cyan lines denote the domain of the CGP.

Figure 11. Daily composites of the anomalies of (a) T_{2m} (K) and (b) 850 hPa geopotential height (gpm) and horizontal wind vectors (m s^{-1}; grey) from the ERA-Interim averaged over dusty days in JJA from 2002-2015. Blue and red contours in (b) denote 1560 gpm in the climatology (2002-2015) and during dusty days, respectively. Areas significant at the 95% confidence level are dotted. Wind vectors significant at the 95% confidence level are plotted in green. Black boxes denote the CGP region.

Table 1 Correlations between friction velocity (U^*) and CIN, CIN and 2 m temperature (T_{2m}), T_{2m} and U^*, T_{700}-T_{dp} (the differences between air temperature at 700 hPa and 2m dew point temperature) and CIN, T_{700}-T_{dp} and U^* for all days in JJA from 2002 to 2015 (1288 days), days when fine dust concentration is available (431 days), and dusty days (52 days). All values are significant at the 95% confidence level (t-test) except those listed in italic.

Variables	All days in JJA	Available days	Dusty days
U^*, CIN	-0.54	-0.54	-0.44
CIN, T_{2m}	-0.59	-0.59	-0.39
T_{2m}, U^*	0.39	0.37	*0.19*
CIN, T_{700}-T_{dp}	-0.59	-0.62	-0.59
T_{700}-T_{dp}, U^*	0.37	0.38	*0.14*

Table 2 Correlations between U^* and CIN, CIN and vertical wind speed at 850 hPa (w850), w850 and U^* during dusty days in JJA from 2002 to 2015. All values are significant at the 95% confidence level except the value significant at the 90% confidence level is labeled with a "+" (t-test).

Variables	Dusty days
U^*, CIN	-0.44
CIN, w850	0.28^+
w850, U^*	-0.32

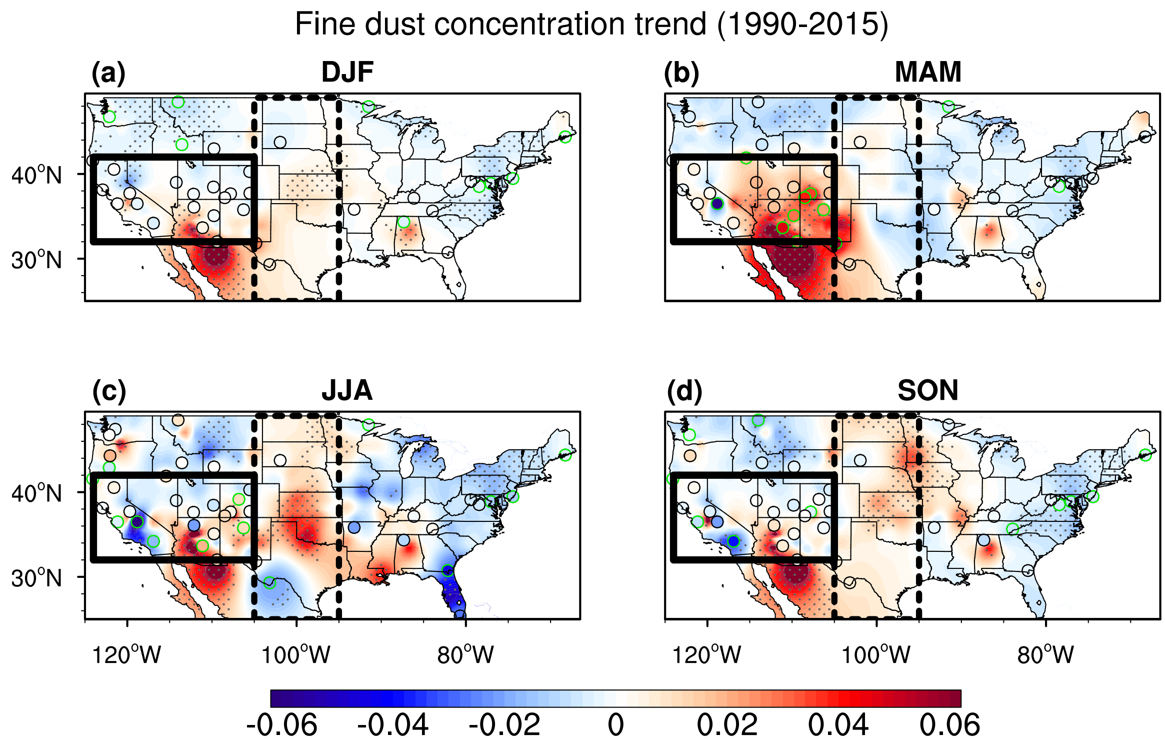


Figure 1. Trend (shading) of fine dust concentration (μg m^{-3}) from 1990 to 2015 in (a) DJF, (b) MAM, (c) JJA, and (d) SON from IMPROVE gridded data. Dotted areas are significant at the 95% confidence level. The colored circles show the trend at IMPROVE stations with consecutive records for at least 23 years during 1990-2015. Circles with green outlines denote that the trend is significant at the 90% confidence level. Black boxes denote the averaging areas of the southwestern U.S. (solid) and the Great Plains (dashed).

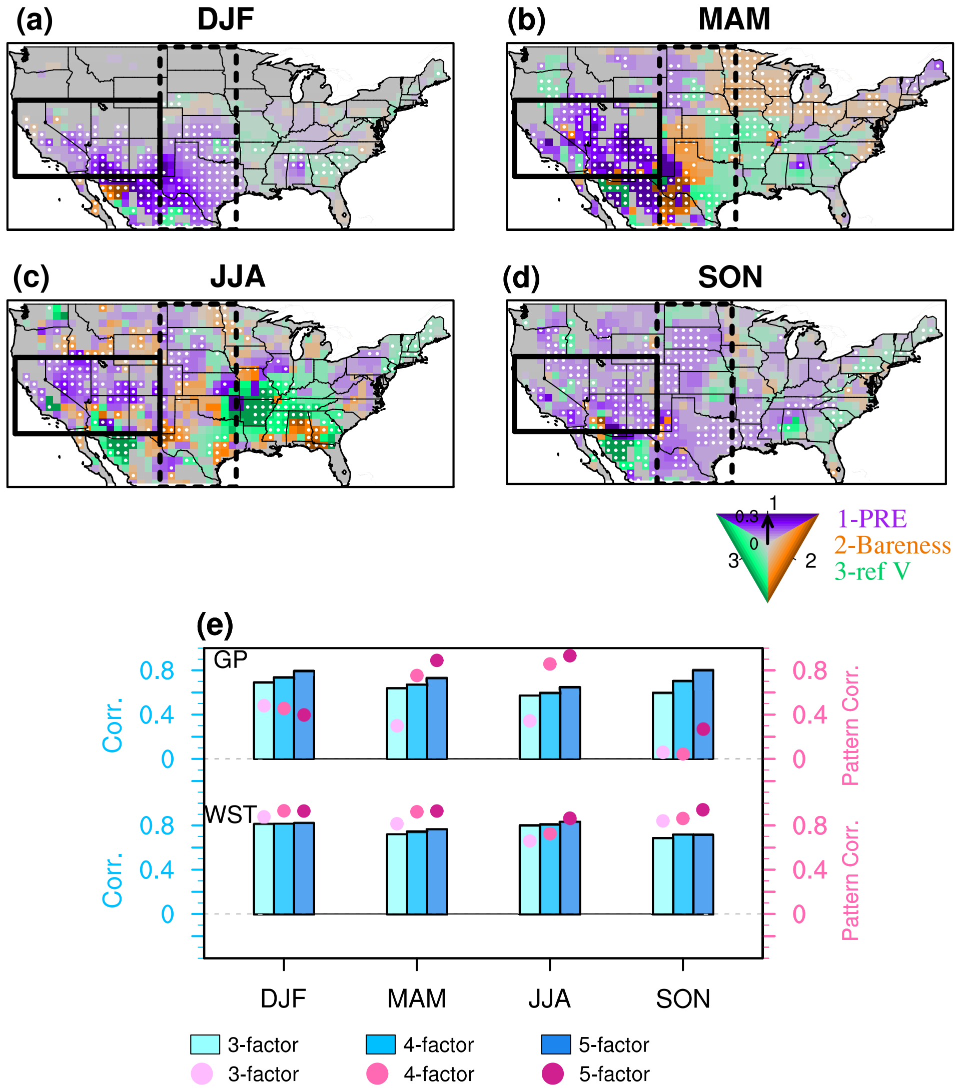
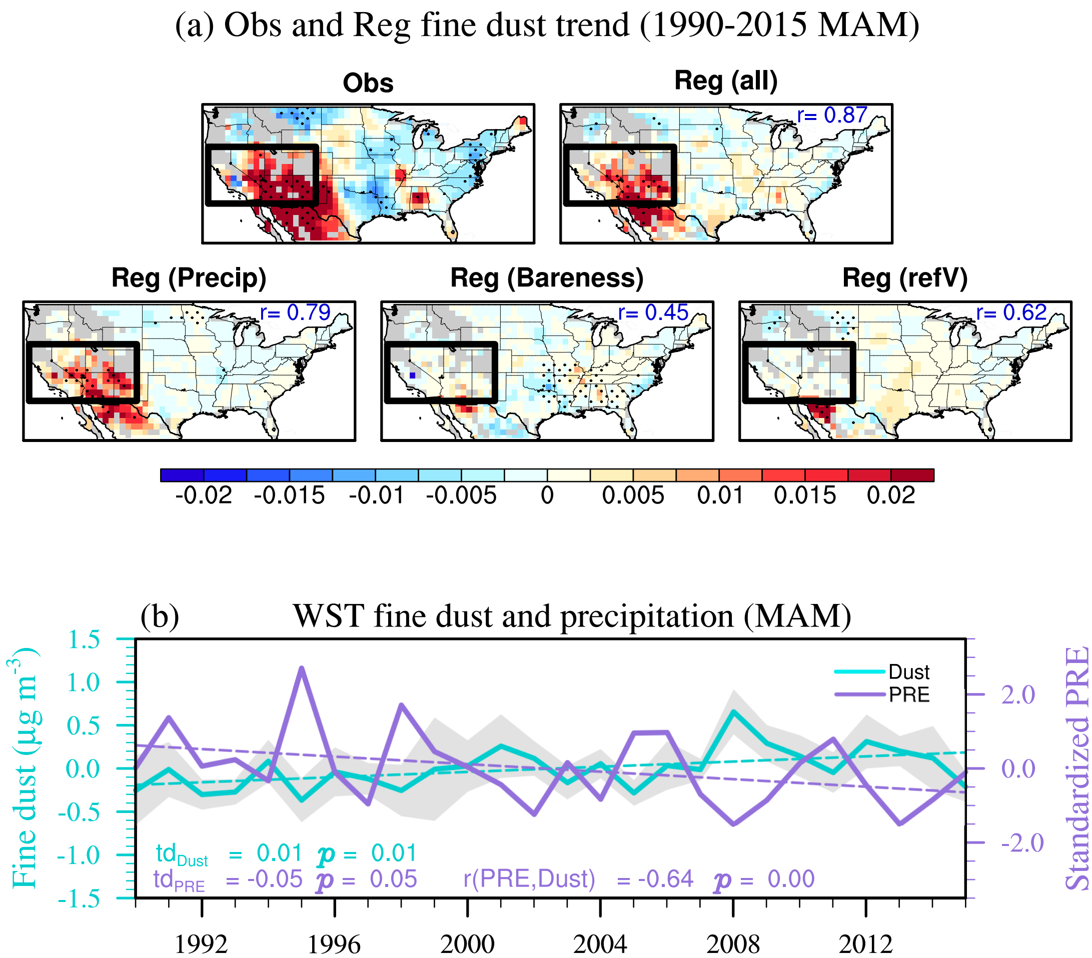


Figure 2. (a)-(d) Multiple linear regression coefficients calculated by regressing fine dust concentration from 1990-2015 onto standardized precipitation (purple), bareness (orange), and surface wind (green). Color denotes the most influential factor at each grid (i.e., the largest regression coefficient in absolute value among the three), while saturation of the color shows the magnitude of the coefficient (0 to 0.3). Areas significant at the 95% confidence levels are dotted. (e) Bar-plot showing the correlations between observed regional mean fine dust concentration and the reconstructed concentration using 3, 4, and 5 controlling factors (light, median, and deep blue), and pattern correlation between trends from the observation and from reconstructed fine dust using 3, 4, and 5 factors (light, medium, and deep pink) in the Great Plains (GP) and the southwestern U.S. (WST, black boxes in a-d). "3-factor" denotes precipitation, bareness, and surface wind, "4-factor" denotes precipitation, bareness, surface wind, and CIN, "5-factor" denotes precipitation, bareness, surface wind, CIN, and CAPE. Black boxes denote the averaging areas of the WST (solid) and GP (dashed).



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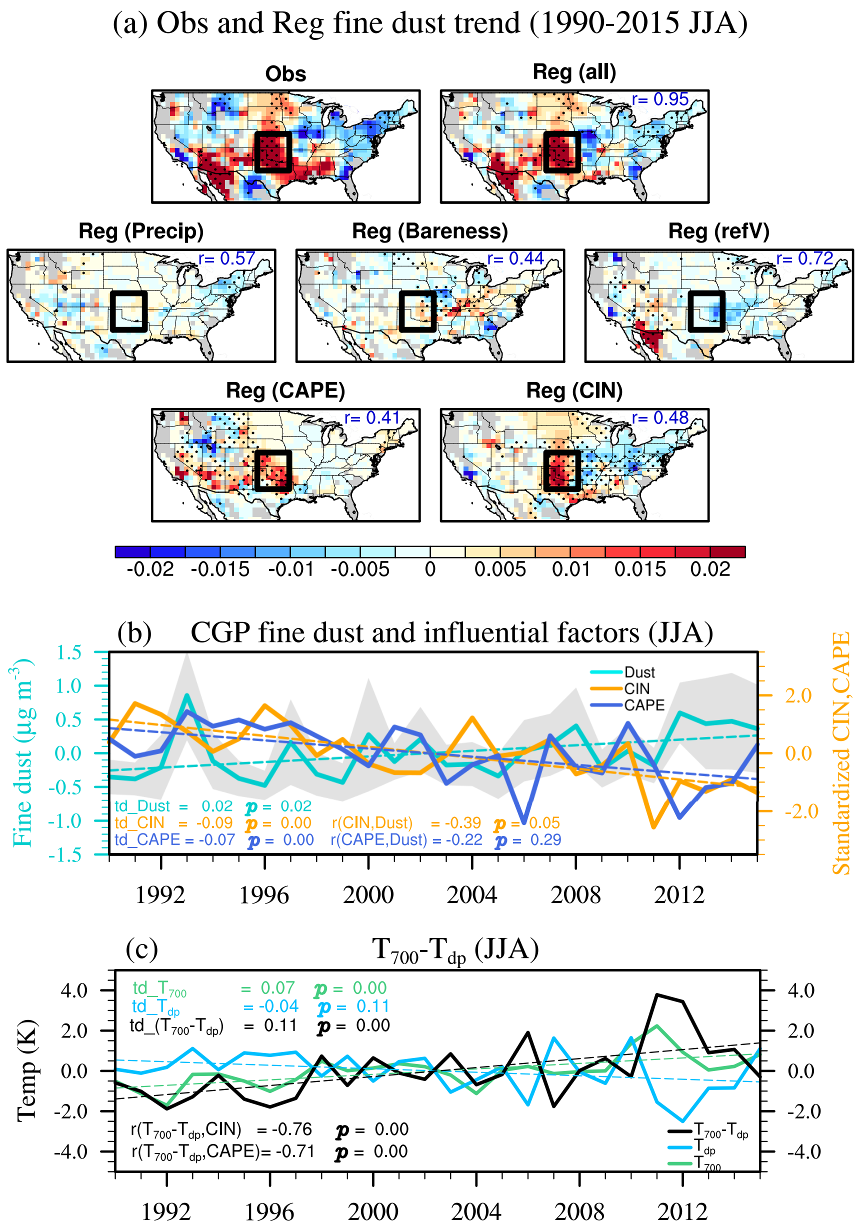

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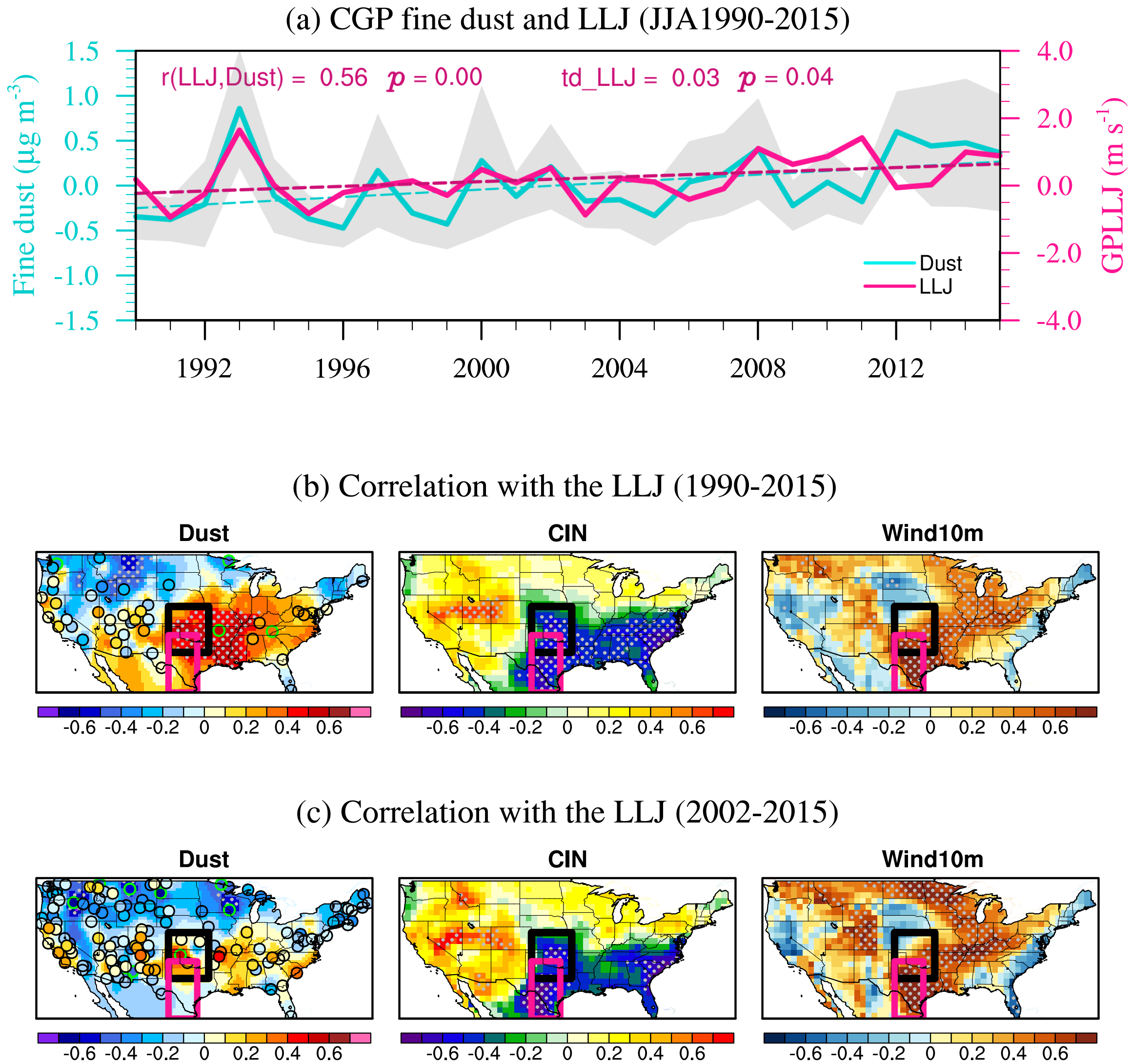

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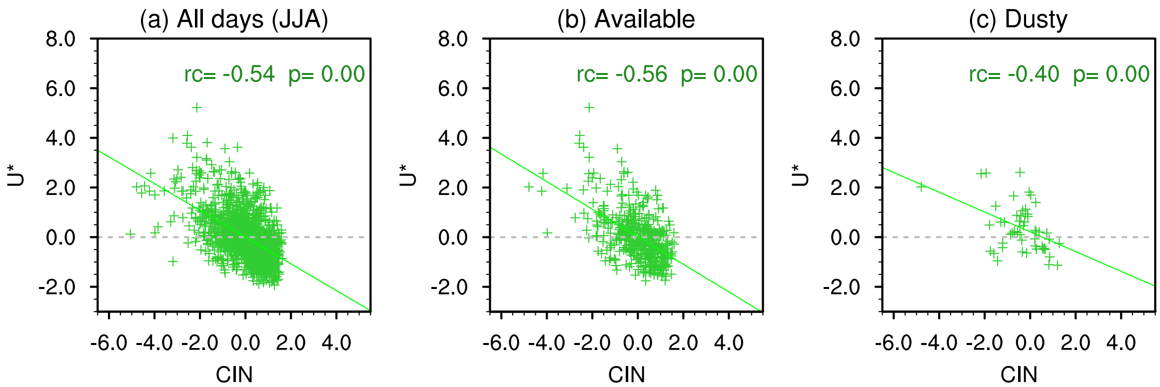

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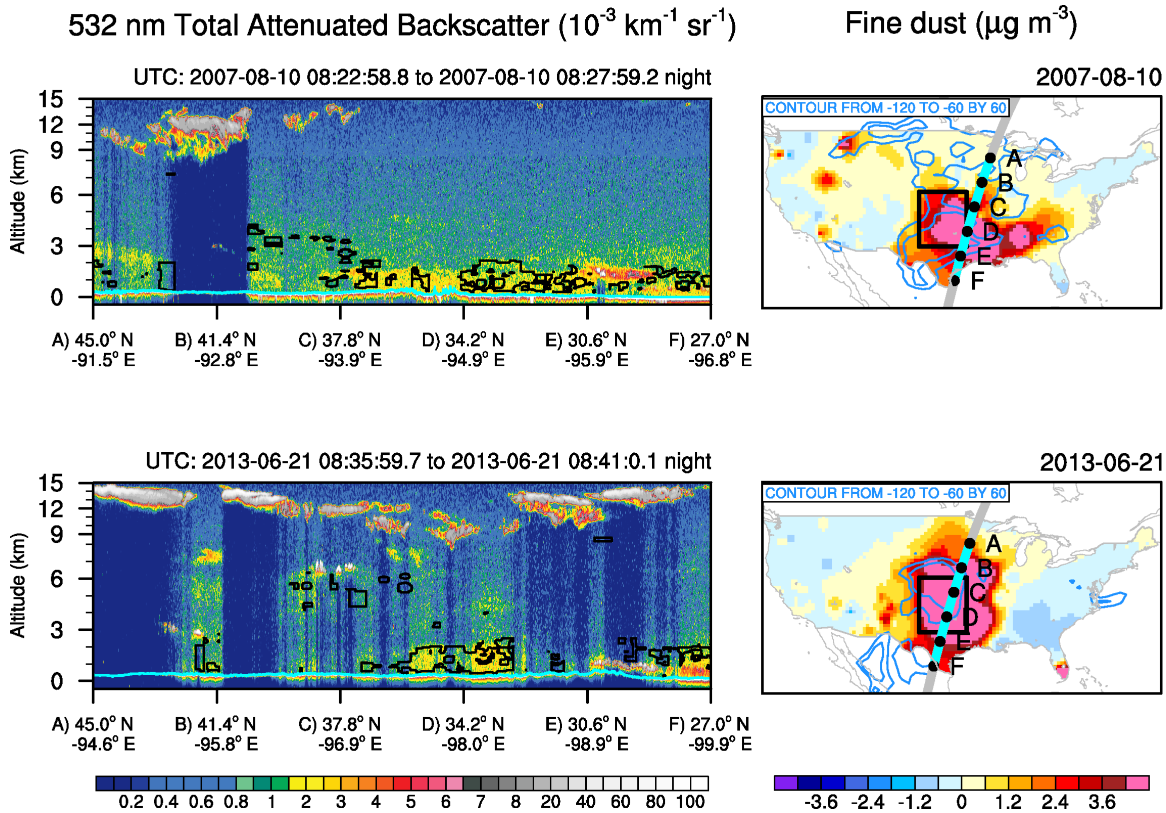

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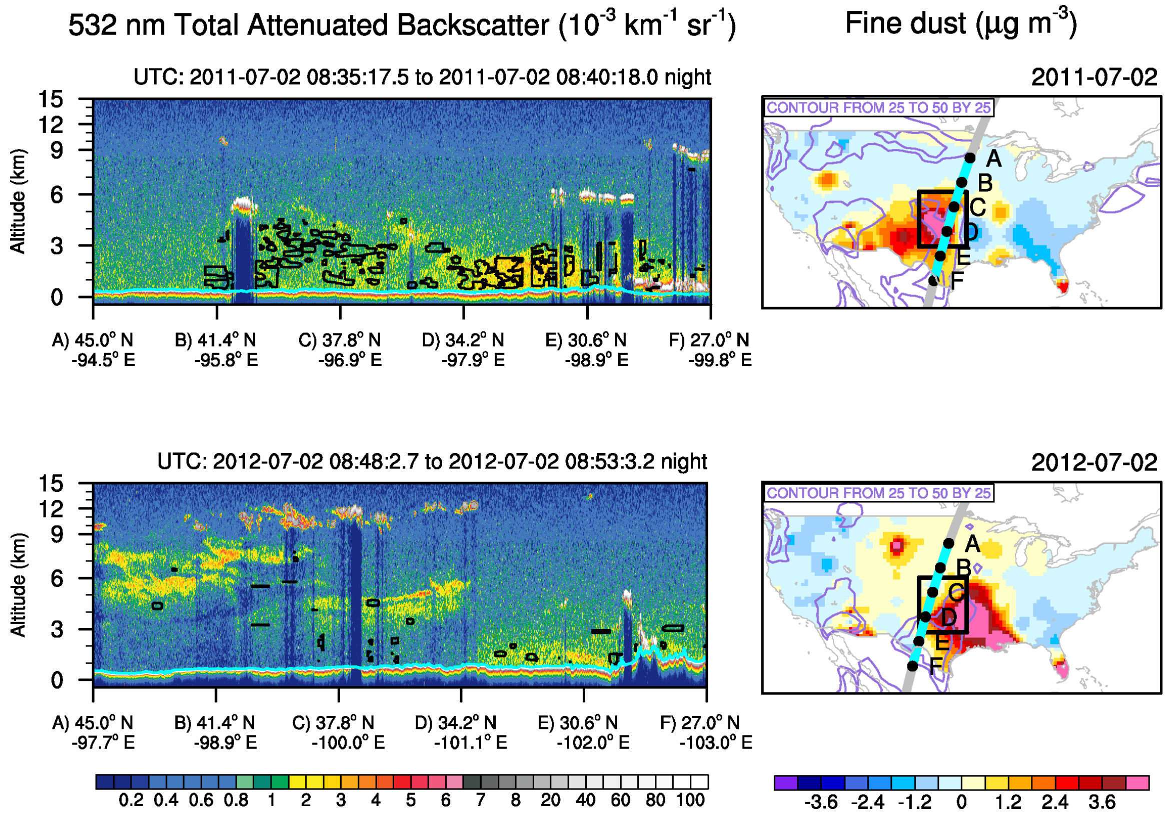

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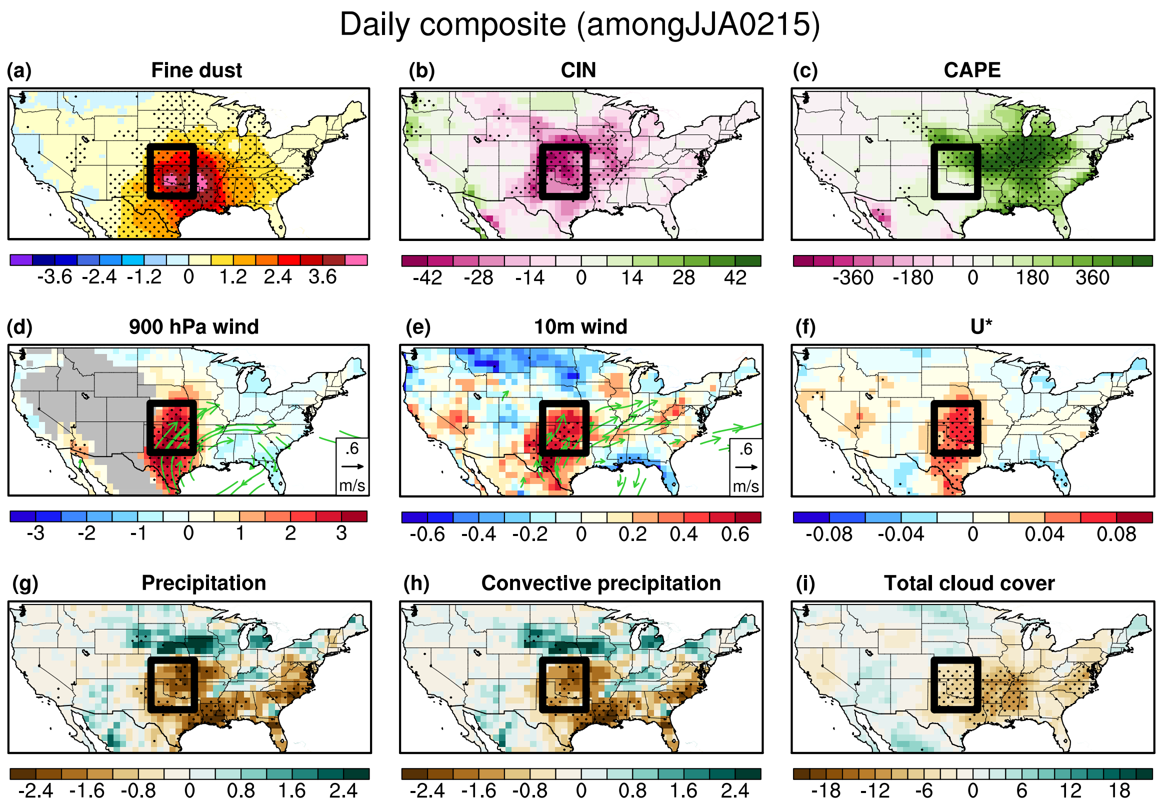

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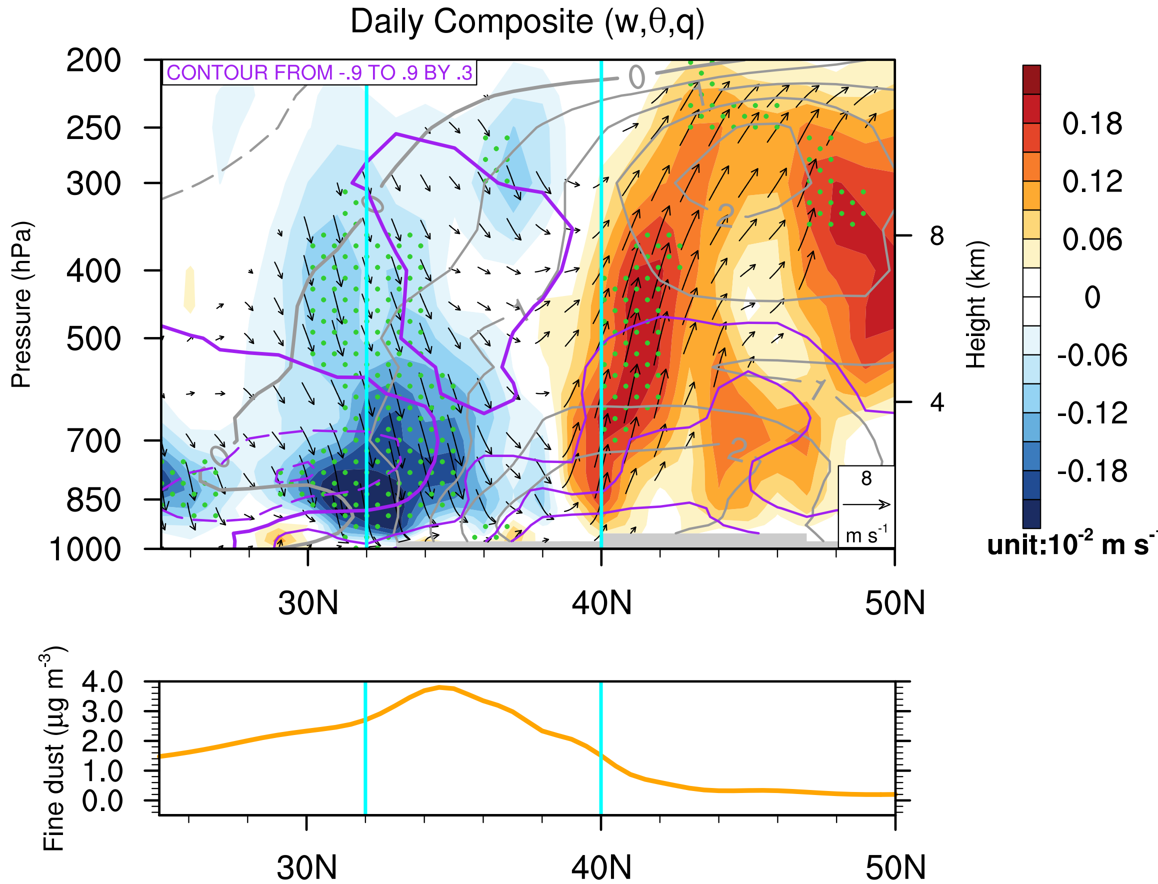

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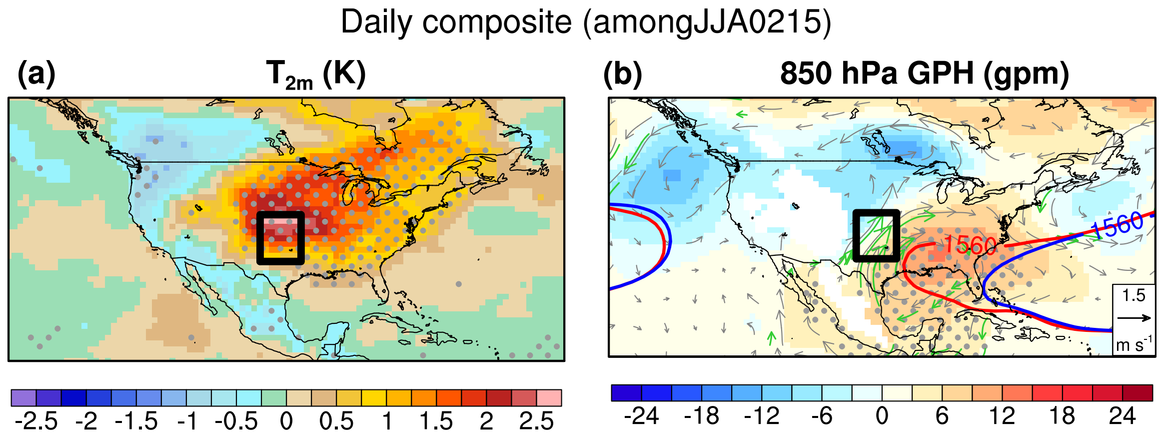

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