Atmos. Chem. Phys. Discuss., 13, 14195–14220, 2013
www.atmos-chem-phys-discuss.net/13/14195/2013/
doi:10.5194/acpd-13-14195-2013

Atmospheric Chemistry and Physics
Discussions
Open Access

Characteristics of dust storm events over the western United States

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Received: 8 April 2013 – Accepted: 11 May 2013 – Published: 30 May 2013

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

Abstract

In order to better understand the characteristics of dust storm processes over the western United States, available dust storm events reported by media or recorded by NASA earth observatory are classified into four types based on the prevailing weather systems. Then these four types of dust storm events related to cold fronts, downbursts, tropical disturbances, and cyclogenesis and their selected typical representative events are examined to explore their identifiable characteristics based on in-situ and remote sensing measurements. We find that the key feature of cold front-induced dust storms is their rapid process with strong dust emissions. Events caused by rapid downbursts have the highest rates of emissions. Dust storms due to tropical disturbances show stronger air concentrations of dust and last longer than those caused by cold fronts and downbursts. Finally, dust storms caused by cyclogenesis last the longest. The analysis of particulate matter records also shows that the relative ratio of PM_{10} (size less than 10 µm) values on dust storm-days to non-dust storm-days is a better indicator of event identification compared to previous established indicators. Moreover, aerosol optical depth (AOD) measurements from both in-situ and satellite datasets allow us to capture dust storm processes. We show that MODIS AOD retrieved from the deep blue data better identify dust storm-affected areas and the spatial extension of event intensity. Our analyses also show that the variability in mass concentrations during dust storm processes captured only by in-situ observations is consistent with the variability in AOD from stationary or satellite observations. The study finally indicates that the combination of in-situ and satellite observations is a better method to fill gaps in dust storm recordings.

1 Introduction

The western United States is an important source of global dust emissions (Woodward, 2001; Tanaka and Chiba, 2006). Main observing networks over the western US have

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included or collected airborne dust into their records or samples. For example, near-surface dust has been quantitatively sampled as total aerosol mass concentrations by the Interagency Monitoring of Protected Visual Environments (IMPROVE) network and the US Environmental Protection Agency (EPA) Air Quality System (AQS). Similarly, the optical properties of dust weather events are recorded as aerosol optical depth (AOD) measurements by the Aerosol Robotic Network (AERONET) (Holben et al., 1998). In addition, a number of space-borne instruments have been used in satellites to capture optical depth, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Remer et al., 2005), Multiangle Imaging Spectroradiometer (MISR) (Kahn et al., 2009), and Total Ozone Mapping Spectrometer (Torres et al., 2002). Although dust has been recorded by a variety of observing systems, it is still difficult to quantify dust events because other aerosols (e.g. wildfire, industrial emissions) that have similar physical properties are also sampled or recorded together in the measurements taken. As a result, a complete or consistent dust event records is unavailable for the public and scientific community.

As an extreme event, a dust storm is a major natural disaster that has affected both social life and public health in recent decades (Prospero, 1999; Tong et al., 2012). In the long term, frequent dust storms can affect climate in addition to air quality and health (Zhao et al., 2012). The media have reported all kinds of losses for people in the western US due to dust storms in the past decade. National Aeronautics and Space Administration (NASA) earth observatory also captured some dust storm processes over the western US. However, compared with regular blowing dust weather, dust storm events featuring high dust concentration levels are relatively easy to identify from measurements. Indeed, a series of studies using different observations has already been carried out in order to examine the particular characteristics of dust storms (Prasad and Singh et al., 2007; Hahnenberger and Nicoll, 2012).

For instance, the characteristics of dust storm events have previously been examined based on stationary aerosol concentration data from the IMPROVE network (Bell et al., 2007; Tong et al., 2012). The optical properties of dust storm events have also been

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analyzed based on laser detection in AERONET (Chin et al., 2009; Kim et al., 2011). Further, satellite data from MODIS and MISR have been used to retrieve the AOD measurements of dust storm events (Baddock et al., 2009; Waggoner and Sokolik, 2010; Ginoux et al., 2012). Some studies have noted deficiencies in using individual observation datasets in dust analyses (Tong et al., 2012; Kim et al., 2012), while some others have used AERONET and satellite datasets together to understand the optical properties of dust storm events (Lee et al., 2012). However, the identified physical characteristics and time series of dust storm events based on different datasets largely vary. As such an accurate dust climatology and coordinated methods to unify different observational records are still unavailable.

To better understand the characteristics of dust storm processes over the western US, in this study we classified all available dust storm events reported by media or recorded by NASA earth observatory over the western US, and then analyzed a series of typical dust storm events and their identifiable characteristics based on the application of different measurements. Specifically, we integrate stationary aerosol concentration data from the IMPROVE network, the US EPA AQS datasets, the stationary laser-detected optical information for aerosols provided by the AERONET network, and the AOD observations from the deep blue data of MODIS satellites. The differences among these methods are then compared, and the results are linked and assembled in order to offset the deficiencies in using individual datasets. This study aims to develop a comprehensive and objective methodology by integrating measurements from various observing networks in this way in order to support further reconstruction of merged dust climatology for climate studies and model verification.

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2 Methodology

2.1 Event classification

Dust storms have seriously affected the western US and beyond in recent decades. Detailed reports on historical events can even be dated back to the 1930s (Schubert et al., 2004). Main focus in this study is dust storm events in the past decade, since associated in-situ and remote sensing measurements are comprehensive enough to make better analysis on the identifiable characteristics of dust storms during this period. Without specific and consistent recording, we have to collect dust storm cases over the western US from internet-based media reports and some significant events recorded by NASA earth observatory. A comprehensive events pool is developed including 57 reported dust storm events.

Dust storms differ in size, duration, and intensity. Previous studies suggested that the prevailing meteorological conditions play a major role in determining these characteristics of dust storms (Shao, 2002). With further examination on these reported dust storm events, we found that these dust storms in the western US are mainly influenced by weather patterns, including fronts, downburst, tropical disturbances, and cyclogenesis. The influence of meteorological regimes on dust storms is complex, which is also a key issue for dust modeling study. Besides surface conditions, the friction velocity (mainly determined by surface wind speed) is the key factor in determining dust emission (Lei et al., 2005; Lin et al., 2012). Therefore, the intensity of four types of dust storms are mainly influenced by the surface wind resulted from prevailing weather systems. Fronts, mostly cold fronts, are a kind of rapid weather processes that can cause strong wind near the ground and take dust following the movement of fronts. Downbursts are caused by thunderstorms in either wet (rain) or dry (little rain) condition. It features strong downward airflow to the ground, which spreads out in all directions producing strong winds near the surface. Dry downburst can create severe dust storms. Tropical disturbance is a short-term process that can produce strong surface wind in response to the disturbance transported from the tropical region. It can produce weak dust storms

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in tropical regions. Cyclogenesis may last several days and can cause strong surface wind during its developing stage (Rauber et al., 2002), which may cause dust emission near the trough. The meteorological mechanism and classification are also confirmed by previous study on historical events (Brazel and Nickling, 1986). All collected dust storm events are classified in Table 1 based on their prevailing weather systems.

As shown in Table 1, the most common dust storm type in the western US is downbursts, which are typically caused by thunderstorms in which the organized outflow from the downdrafts of decaying thunderstorms blows dust plumes from source regions. These blown dust plumes then take on the appearance of a moving wall of dust called a haboob that spans miles and rises thousands of feet into the air. Dust storm events caused by different weather systems show different intensities and identifiable characteristics in observational systems.

In order to better capture dust storm properties over the western US, we focus on the comprehensive analysis of typical events and statistical description of group characteristics based on the results. Four typical dust storms are selected to represent their types by the maximum availability of recording in datasets: (1) fronts, (2) downbursts, (3) tropical disturbances, and (4) cyclogenesis. Figure 1 shows the visible high-resolution satellite images and sketches of the corresponding weather systems for these dust storms. The comprehensive analysis of these typical events are introduced below. All dust storm events in each group will also be analyzed and discussed along with the corresponding typical events.

2.2 Data analysis

To better understand the characteristics of dust storm events, we analyze the mass concentration and optical properties of these events based on the EPA AQS, IMPROVE, and AERONET datasets as well as the retrieved AOD from the MODIS deep blue dataset. Among these datasets, the in-situ IMPROVE data have previously been used to identify dust storm activities (Bell et al., 2007; Tong et al., 2012). By comparison, the EPA AQS dataset has a better spatial and temporal coverage for mass concentrations of PM_{10} and $PM_{2.5}$ (particulate matter with a size less than 10 and 2.5 µm, respectively), which is beneficial in mass concentration analysis. Both IMPROVE and EPA AQS dataset are employed in mass concentration analyses including examining the statistic properties for each type. Since the increase in aerosol concentrations may be caused by wildfire and industrial emissions, we need to reference the United States Geological Survey (USGS) wildfire record and EPA AQS air quality observations to prevent the large noise to analyses.

Another issue for stationary analyses is the selection of reference sites. In this study, the reference sites are chosen based on the locations of air quality sites and the availability of observational data (AQS, IMPROVE). We try to find sites near the center of dust storm affecting region, but in some cases, the sites that best fit the requirements are still on the edge of affecting region. The relative location may significantly influence the magnitude in mass concentration analyses, although the trend and variability may not be seriously affected. Similar situation is to the stationary analyses of optical properties.

The analysis of optical properties will focus on the linkage with results from mass concentration analyses and using the statistic information for individual dust storm process. Limited by data availability, the optical properties will not extend to the analysis of statistic properties for each type. For optical depth observations, in-situ AOD measurements from AERONET have been used to study dust storm weather events (Chin et al., 2009; Kim et al., 2011; Lee et al., 2012). However, although the AOD from the IMPROVE nephelometer observations have rarely been used, its better temporal resolution may be a good supplement for the missing observations in the AERONET dataset. For satellite data, the MODIS at 550 nm deep blue dataset features in AOD observations over land. The available level 3 (L3) dataset from the Terra and Aqua satellites has the best temporal and spatial coverage for the western US among satellite products, which is an ideal dataset for the identification of dust storms.

For mass concentration analysis, PM_{10} and $PM_{2.5}$ levels are calculated for each dust storm case and the ratio of $PM_{2.5}$ to PM_{10} is also examined. These calculations have

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been carried out in previous dust storm identification studies (Bell et al., 2007; Tong et al., 2012). In this study, however, a group of additional datasets and analyses are employed. These include:

1. The ratio of the dust storm-hours PM_{10} (or $PM_{2.5}$) level to the non-dust storm-day PM_{10} (or $PM_{2.5}$) level, which is represented by the average of the lowest 80 % percentile PM_{10} (or $PM_{2.5}$) concentration recorded in the month and calculated based on AQS hourly PM mass concentration data to understand diurnal variation;

2. The in-situ AOD data from the AERONET and IMPROVE nephelometers, which are analyzed to examine the daily and diurnal variability of AOD during the dust storm process; and

3. The AOD measurements from the MODIS L3 dataset, which are used to determine the strength and spatial affecting range of dust storm events.

4. The variation in AOD during dust storm events is also analyzed from the statistical information derived from the MODIS data.

The target of this study is to explore the key characteristics of dust storms in order to describe the common and specific features of individual dust storm events. We also pay attention to possible linkages between the mass concentration and optical properties of these events. Statistical values to describe the group feature of all dust storm events in each type are shown as the uncertainty upon analysis of typical events. Based on the analyses described above, an objective, unified, and comprehensive methodology is presented for quantifying the characteristics of the typical dust storms selected in this study.

3 Results

3.1 Characteristics derived from mass measurements

Figure 2 shows the daily averaged concentrations of PM_{10} and $PM_{2.5}$ at dust storm-affected sites during these events. With reference to the US EPA national ambient air quality standards, the daily averaged concentration of PM_{10} is above the suggested limit of 150 µg m^{-3} in downbursts (D2). The $PM_{2.5}$ level is also above the standard in D2. Previous studies have shown that haboobs, which are caused by the strong wind in downbursts, are the most severe dust storms of the four studied types (Brazel, 1986). These usually feature rapidly moving dust walls. Cold fronts-related dust storms (D1) are also very strong, with a daily averaged PM_{10} level above 100 µg m^{-3}. By contrast, the dust storms caused by tropical disturbances (D3) and cyclogenesis (D4) are relatively weak.

From Fig. 2, it is clear that a high PM_{10} value is a common feature for all dust storms. As shown in black lines, the statistical feature for each kind of dust storm events clearly varies and close to the characteristics of corresponding typical events. The differences in strengths among individual event or different groups are mainly caused by the intensity of the prevailing weather systems. In addition, the relative location of the observing station with respect to the distribution of dust strengths is another important factor that may affect the strength levels. The erodibility of the land surface condition in the source region also influences the intensity of dust storm events.

Based on various daily and hourly PM_{10} and $PM_{2.5}$ mass concentration records during dust storm events, Fig. 3 illustrates the ratio of the dust storm-hours PM_{10} (or $PM_{2.5}$) level to the non-dust storm-day PM_{10} (or $PM_{2.5}$) level, as described earlier, and the ratio of dust storm-day $PM_{2.5}$ to PM_{10}. It is evident that the former ratio for the PM_{10} level is between 4 and 7 in typical case studies. The corresponding group feature is above 3, which suggests a common characteristic for dust storm events in affected regions. The similar ratio for the $PM_{2.5}$ level is not as uniform, however. For example, the ratios for

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D2 and D4 are high, while they are very low for D1 and D3. These differences may be caused by wildfire and industrial emissions, which mainly influence $PM_{2.5}$ concentration levels, but not those of PM_{10}. The relative low mass concentration of $PM_{2.5}$ may also cause uncertainties in the ratio of $PM_{2.5}$. In terms of the mass ratio of $PM_{2.5}$ to PM_{10} (Bell et al., 2007; Tong et al., 2012), a low ratio is associated with dust storms as suggested by previous studies. However, this ratio may suffer from its intrinsic deficiency as an identification standard, because the ratio for regular days may have already been very low at some sites.

To further understand changes in mass concentration during dust storm events, we next analyze the 48 h variation in PM_{10} concentrations around the reported dust stormday. Figure 4 shows the variation in PM_{10} hourly concentrations based on US EPA AQS measurements. D1 leads to a sharp increase in PM_{10} to 1000 $\mu g\,m^{-3}$ within less than two hours; however, the high value lasts only for a couple of hours, indicating an intensive and fast process. D2 shows a similar characteristic with an even higher intensity and faster process. Both D1 and D2 occur in the afternoon, when the boundary layer becomes unstable. D3 occurs in the early morning, when surface winds over land become active, and it lasts for 6 h with a peak strength of 1000 $\mu g\,m^{-3}$ according to PM_{10} records. D4 shows dust emission peaks with relatively weak strengths in the afternoon and night hours. This may be associated with the relatively slow development of surface instability in cyclogenesis and diurnal cycle of boundary layer.

The group features of all types of dust storm events are summarized in Table 2. Dust storm caused by downburst is the fastest process with peak PM_{10} concentration up to 3500 $\mu g\,m^{-3}$. The type caused by cyclogenesis in middle latitude is a kind of mild processes, which may last up to 21 h. And the peak strengths can be very weak down to 130 $\mu g\,m^{-3}$. These specific features potentially increase the difficulty to identification. The type of dust storms caused by fronts is also strengthful and frequently occurs in the central west plain region according to Table 1. The middle-strength dust storms caused by tropical disturbance did not occur so often in our study pool, which usually

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occurs in California or near the boundary between US and Mexico. This type of dust storms usually last 3 to 7 h.

3.2 Characteristics derived from optical measurements

Owing to the data limitations of optical observations, it is impossible to examine the optical features for all dust storm cases. Since we have examined the group features of all cases in above mass concentration analysis, therefore, for optical analysis, we will focus on these (1) typical cases representing each type, (2) the linkage of their optical feature with mass concentrations, and (3) statistic optical features in satellite retrieved AOD for individual case. Figure 5 shows the variability in AOD from in-situ observations during dust storm events. For stationary analysis of optical features, we use the nephelometer-observed AOD values from the IMPROVE network for D1 and D2, while AERONET-observed AOD is used for D3 but no suitable in-situ AOD data could be found for D4.

From Fig. 5, AOD concentration peaks last for about two hours for both D1 and D2, which is similar to the PM_{10} results shown in Fig. 4. For D3, the AERONET-observed AOD value during dust concentration peak hours is close to the peak value for D1, which is also consistent with the PM_{10} concentrations. These results suggest that the IMPROVE nephelometer 530 nm AOD is comparable to AERONET 500 nm AOD, which is in agreement with previous studies (Reference: http://alg.umbc.edu/neph/Neph_AOT.html).

Satellite-retrieved AOD on the specific dust storm day is augmented for the analysis of events. Figure 6 shows the daily mean AOD over land from the MODIS deep blue (550 nm) data on four typical dust storm-days. Significant changes in aerosol optical depth over the western United States may be caused by dust emission, wildfire and severe air pollution episodes. We first reference to the AQS air quality observations (SO_2, NO_2, CO) on that day to prevent high AOD days due to air pollution episodes. Based on the regular SO_2, NO_2 and CO levels, these four days are excepted from anthropogenic pollution episodes. Wildfire records from USGS have also been used

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to prevent the contribution from wildfire. For D1, the only high AOD area occurs near the border of Texas and New Mexico as circled by a solid line, which captures the affected area of this event. Caution must be exercised when using satellite images to identify dust events, as not all high MODIS AOD values represent dust storm events. Wildfires may also contribute to the AOD in satellite images. For example in D2, it is noted that two regions feature high AOD values: one over Arizona circled by a solid line and the other circled by a dashed line over a larger area across the border regions of New Mexico, Texas, Colorado, and Oklahoma. By cross-checking with wildfire records during 2011, it is easy to identify that the latter was caused by the Las Conchas wildfire, which started on 26 June 2011 and lasted over a month. Additionally, the scattered high values of MODIS AOD over California correspond to the dust storm on 5 July 2011 captured by local in-situ records. For D3, the high AOD value presented over southern California captures event characteristics. Similar to D1 and D3, the high value of MODIS AOD shown over the Texas area is identified clearly as D4.

These analyses show that satellite images can provide important information for the identification of dust storms, although contaminated signals may occur because of other environmental events. More importantly, satellite-retrieved AOD can provide useful information on dust storm-affected areas and on the spatial extension of event intensity. It is clear to see that cold front dust storms have a large affected region, while downburst dust storms have high strength. However, it should also be noted that the satellite information is affected by the satellite swath coverage and frequency. For example, some rapid dust storm processes may not be captured by satellites. Therefore, we need to use the statistics computed from these satellite AOD values to capture more information and achieve a better understanding.

Figure 7 shows the satellite data retrieved to examine the variability in AOD during the dust storm process. The bar chart presents the values of the mean, maximum, minimum, and standard deviation for daily satellite observations. The mean values of MODIS AOD are comparable in magnitude to those of the in-situ observations of AOD, which may be partially because the latest version of the MODIS AOD dataset was

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calibrated with the in-situ observations (Lee et al., 2012). The only difference is that the satellite value represents a spatial average, while the in-situ observation is for a specific location. Therefore, the stationary AOD and concentration measurements should be associated with a satellite AOD value between the maximum and minimum. Figure 7 also shows that D1 has the largest variability in satellite AOD records. However, dust emission may distribute unbalanced within a grid cell, and thus can cause the large standard deviation. This property may be a good indicator for dust storm identification. D2 shows a high mean value of AOD with low variability, which indicates that the effect of D2 on air quality is stronger and boarder. Compared with D3, which has a similar mean value, D4 shows the lowest variability in the AOD records. According to these mass concentration data, this feature shows the whole grid is under the influence of this dust storm event.

4 Discussion and conclusion

In order to better understand the characteristics of dust storm processes over the western US, we collect and classify available dust storm events reported by media or recorded by NASA earth observatory into four types based on the prevailing weather systems. Then these four types of dust storm events related to cold fronts, downbursts, tropical disturbances, and cyclogenesis and their selected typical representative events are examined to explore their identifiable characteristics based on in-situ and remote sensing measurements. The result shows that both in-situ observations for mass concentrations and AOD observations from stations and satellites can capture the variability in dust storms. The analyses show common characteristics for all dust storm events including high PM_{10} levels, large diurnal variability in PM_{10} concentrations, relatively low $PM_{2.5} : PM_{10}$ ratios, high AOD values recorded by satellites, and large standard deviations in satellite-retrieved AOD. The result also suggests specific characteristics for different types of dust storms. In summary, the typical characteristic of front-induced dust storms is a rapid process with strong dust emissions. Dust storm caused by rapid

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downbursts is the strongest, with highest levels of dust emissions, and is also a rapid process. Dust storms due to tropical disturbances show strong air concentrations of dust and lasts longer than those by cold fronts and downbursts. Cyclogenesis induced dust storms is the longest lasting dust storm, since the cyclogenesis tend to be stationary.

The analysis of criteria for the identification of dust storms indicates that the relative ratio of PM_{10} between the level on the dust storm-day and the mean level may be a better indicator of dust storm events based on the in-situ mass observation datasets. Our analysis also shows that high values of this ratio exist for all types of dust storms irrespective of the large differences in the strengths of the events.

MODIS-retrieved AOD from the deep blue algorithm can improve the understanding of dust storm processes and dust storm identification. Besides the common characteristics found in mass concentration data, satellite data provide specific information about dust storm-affected areas and the spatial extension of event intensity. By linking the statistical information derived from satellite AOD data with the variability presented in mass observations, we find that more detailed information about dust storm processes can be retrieved from the statistic properties of AOD provided by satellite datasets. In addition, this study also suggests that wildfire emissions are a significant noise to dust storm identification in the MODIS AOD dataset and can be filtered according to existing archives of wildfire records.

For the identification of dust storms, the combination of in-situ and satellite observations is a good method to fill gaps in dust storm records. The major problems with existing in-situ datasets are their sparse spatial coverage and intermittent temporal continuity, and these deficiencies impact directly on the construction of dust storm climatology. By analyzing in-situ mass concentration data from both the EPA-AQS and the IMPROVE networks, we provided a clear explanation and advanced our understanding of the typical types of dust storm processes. Previous analyses of dust storms mainly rely on only the IMPROVE network, which contains the composition of aerosols. It is important to recognize that EPA AQS and MODIS AOD data can provide alternative,

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and even better, information on temporal variation and spatial coverage. We want to stress in this paper that assembling in-situ observations and satellite AOD together improves the identification of dust storm events in the western US.

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Table 1. Classification of reported dust storm events over the western US.

Group	Weather System	Count	Dust Storm Events (mm/dd/yyyy-State)
1	Fronts	8	12/15/03-TX; 02/19/04-TX; 11/27/05-TX; 10/04/09-WA; 05/03/10-WA; 04/15/11-OK; 10/18/12-KS; 11/10/12-CO-KS; 01/11/13-CO-KS; 08/05/12-OR; 06/04/12-ID; 05/09/04-MN; 07/06/09-CO
2	Downburst	33	04/15/03-TX; 07/23/03-Utah; 08/22/03-AZ; 04/12/06-AZ; 06/06/06-AZ; 04/28/07-AZ; 12/23/07-AZ; 03/14/08-NM; 03/04/09-Utah; 03/07/09-Utah; 04/03/09-AZ; 04/15/09-Utah; 12/30/10-TX; 07/05/11-AZ; 07/07/11-AZ; 07/31/11-AZ; 08/18/11-AZ; 08/26/11-AZ; 02/23/12-Utah; 04/14/12-NM; 04/30/12-TX; 05/09/12-AZ; 06/26/12-AZ; 06/27/12-AZ; 07/21/12-AZ; 07/23/12-AZ; 07/30/12-AZ; 09/06/12-AZ; 01/29/13-NM; 02/09/13-NM; 02/19/13-NM; 08/31/07-ID; 11/04/11-AZ
3	Disturbances	3	04/18/04-CO; 04/12/07-CA; 03/18/08-TX
4	Cyclogenesis	13	01/01/06-TX; 04/06/06-TX; 02/24/07-TX; 01/29/08-TX; 01/22/12-TX; 02/20/12-TX; 10/16/12-WY; 03/26/12-WY

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Table 2. Statistic properties of peak dust storm processes for each type.

Group	Dust Storm Lasting Time Range (Hours)	Peak PM_{10} Range ($\mu g\,m^{-3}$)
Fronts	3–5	431–1765
Downburst	2–5	586–3543
Disturbances	3–7	476–1137
Cyclogenesis	4–21	137–1392

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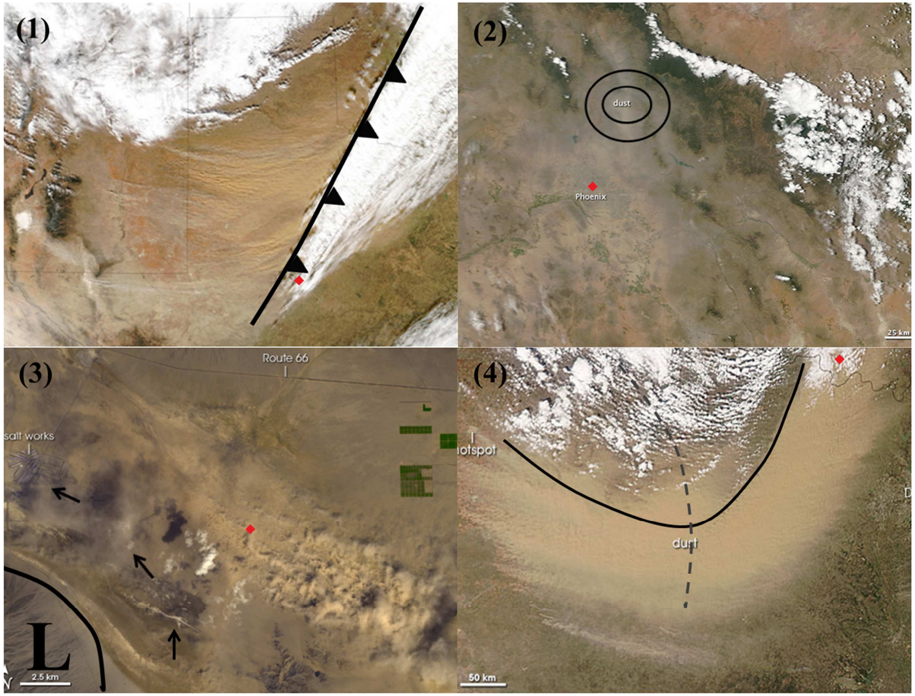

Fig. 1. Four typical dust storms over the western United States. Visible satellite images and corresponding weather systems for them. (1) Dust storm caused by cold front (D1), 15 December 2003 at Texas and Oklahoma border. (2) Dust storm caused by downburst (D2), 5 July 2011 near Pheonix, Arizona. (3) Dust storms caused by tropical disturbances (D3), 12 April 2007 near Amboy, south California. (4) Dust storm caused by cyclogenesis and associated trough cut-off (D4), 24 February 2007 at west of Dallas, Texas. Red signs show the location of available reference air quality sites used in following analyses. (Image credit: NASA earth observatory).

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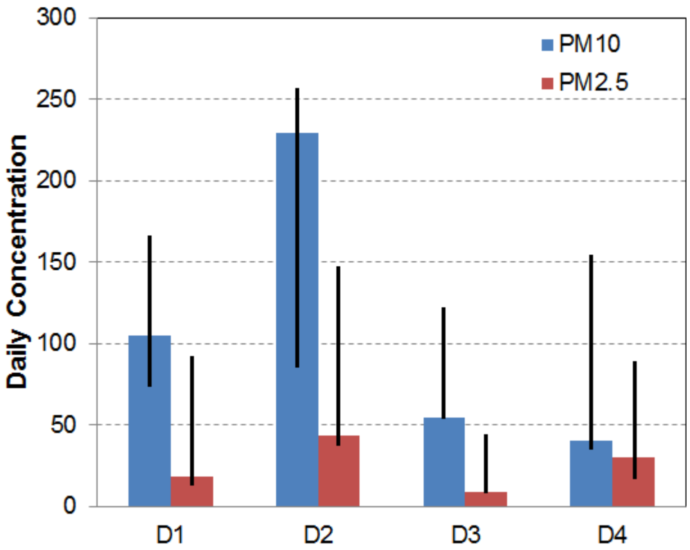

Fig. 2. Daily averaged concentrations of PM_{10} and $PM_{2.5}$ on dust storm days. Data from sites in dust storm affecting regions for four typical events are from IMPROVE network and EPA AQS, D1: use site 480290053 from AQS; D2: use site PHOE1 from IMPROVE; D3: use site SAGO1 from IMPROVE; D4: use site WIMO1 from IMPROVE. Statistic ranges of concentrations for each type are shown in black lines. (Unit: $\mu g\,m^{-3}$).

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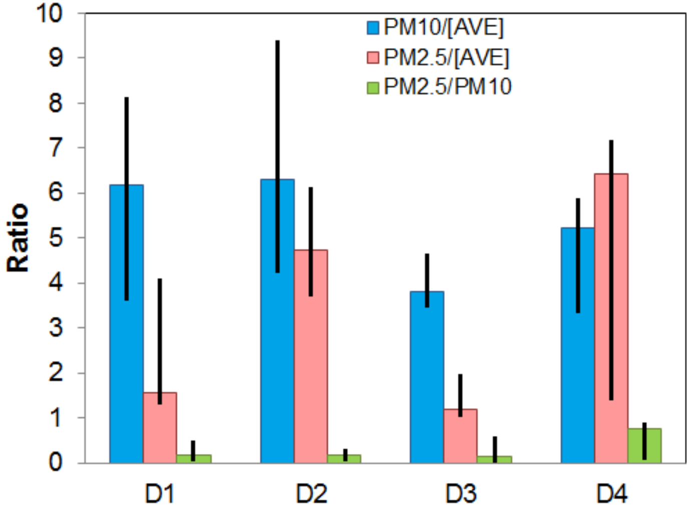

Fig. 3. Ratio of PM (PM_{10} and $PM_{2.5}$) concentrations on the dust storm days over the lowest 80 % percentile of PM concentrations on the month; and ratio of $PM_{2.5}$ concentration over PM_{10} on dust storm days. D1: use site 480290053 records from AQS; D2: use site PHOE1 records from IMPROVE; D3: use site SAGO1 records from IMPROVE; D4: use site WIMO1 records from IMPROVE. Statistic ranges of ratios for each type are shown in black lines.

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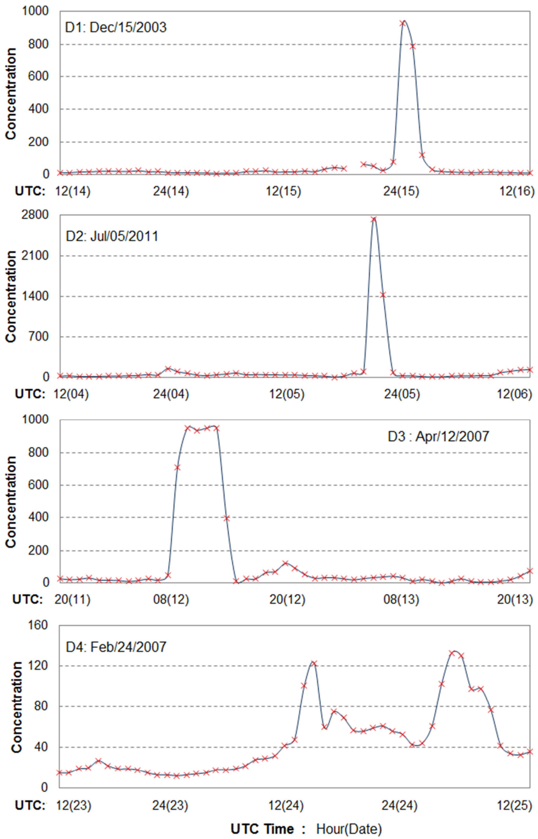

Fig. 4. 48 h PM_{10} hourly concentration change on the dust storm period in impact regions. Data are from EPA AQS. D1: use site 480290053 records; D2: use site 4010 records; D3: use site 60710306 records; D4: use site 480290053 records (Unit: $\mu g\,m^{-3}$).

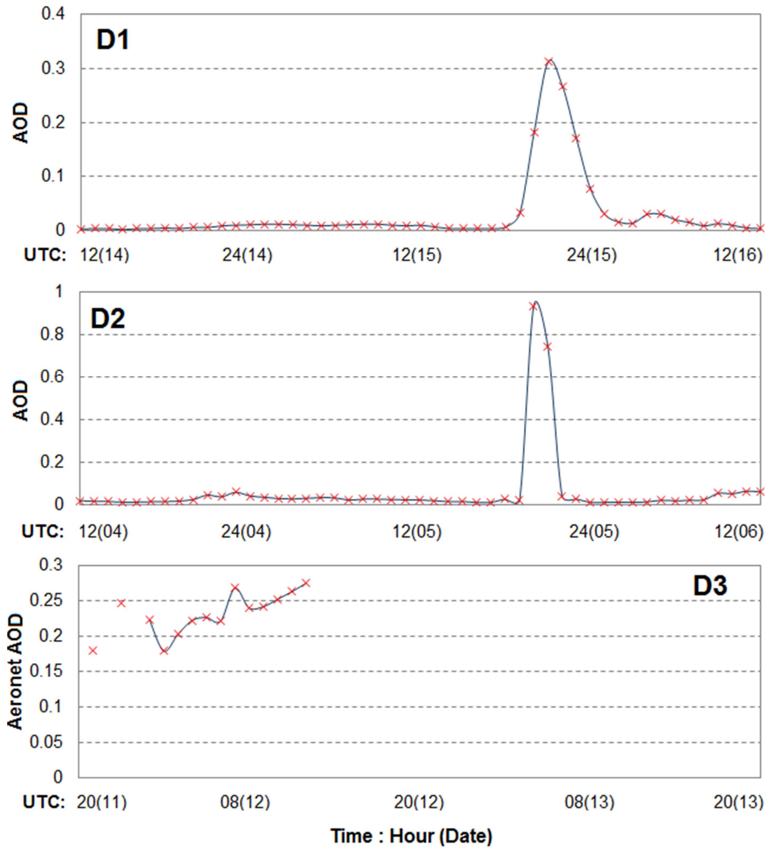

Fig. 5. Stationary observations of AOD variation in dust storm day on sites within the dust storm influencing region. D1: from IMPROVE nephelometer (530 nm) monitor on site BIBE1; D2: from IMPROVE nephelometer (530 nm) monitor on site DYRT1; D3: 500 nm AOD from AERONET monitor on site La_Jolla; D4: no stationary AOD measurements available.

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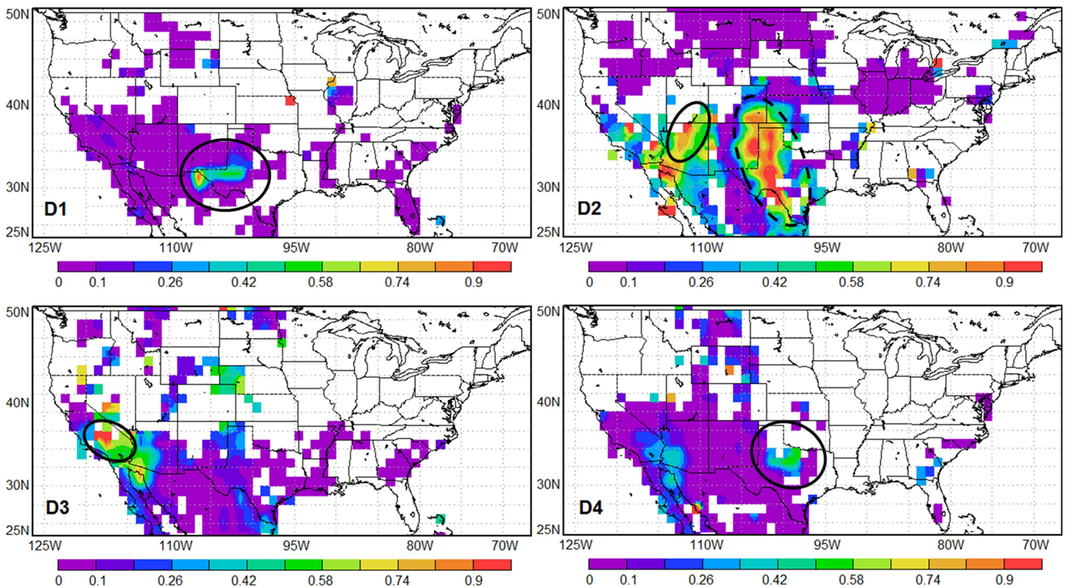

Fig. 6. Mean Aerosol Optical Depth over land on MODIS deep blue (550 nm) data. The result is based on the Level 3 products for the dust storm day (from the combined dataset of Terra and Aqua). Regions circled by solid line are dust storm regions. Regions circled by dashed line are wildfire region according with the wildfire record.

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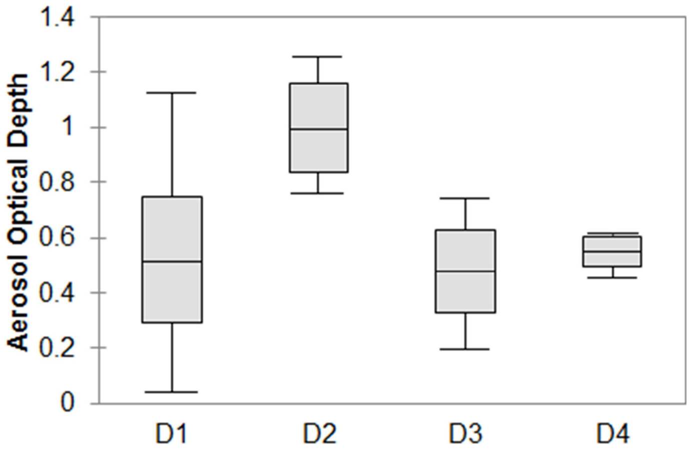

Fig. 7. Statistic characteristics of aerosol optical depth variation in MODIS deep blue (550 nm) dataset during four dust storm days (from the combined dataset of Terra and Aqua). The top bar shows the maximum AOD of the day recorded by satellite; the bottom bar shows the minimum AOD of the day recorded by satellite; the bar in the rectangle shows the mean AOD value of all satellite records during the day; top and bottom edges of the rectangle shows the values at one standard deviation away from the mean AOD.

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