A Case Study of a Typical Dust Storm Event over the Loess Plateau of Northwest China

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Abstract Enhanced observational meteorological elements, energy fluxes, and the concentration of dust aerosols collected from the Semi-Arid Climate Observatory and Laboratory (SACOL) during a typical dust storm period in March 2010 at Lanzhou were used in this paper to investigate the impact of dust aerosols on near surface atmospheric variables and energy budgets. The results show that the entire dust storm event was associated with high wind velocities and decreasing air pressure, and the air changed from cold and wet to warm and dry and then recovered to its initial state. The response of energy fluxes occurred behind meteorological elements. At high dust concentration periods, the net radiation was significantly less in the daytime and higher at night, while the heat fluxes displayed the same trend, indicating the weakening of the land-atmosphere energy exchange. The results can be used to provide verification for numerical model results in semi-arid areas.

Keywords: case study, dust storm, energy budget, Loess Plateau

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1 Introduction

Arid and semi-arid regions account for more than 80% of the total area of Northwest China (Dong et al., 2006). Dust aerosols suspended in the air during strong convection weather in arid and semi-arid regions can influence the energy balance by absorbing and scattering solar radiation and longwave radiation (Qian et al., 1999). The radiative effects of dust aerosols primarily include cooling of the land surface and heating of the aerosol layer (Carlson and Benjamin, 1980). Many studies have been conducted on the regions of China with frequent dust storms (Wang et al., 2006a) that examine the variability of the decadal frequency of these storms (Ding et al., 2003); the physical and chemical properties of dust aerosols and source analyses (Zhang et al., 2008) with their radiative properties (Shen and Wen, 1994); the response of meteorological characteristics near surface (Hu et al., 2002; Ling et al., 2010); the remote sensing of dust aerosol observations and numerical simulation (Wang et al., 2006b; Wei and Shen, 1998), but most of these studies were centered on arid regions.

As a transition zone of the eastern monsoon region and the inland arid region from southwest to northeast, the semi-arid region of China is highly unstable in its dynamics, showing the properties of mutation, sensitivity, and recoverability, and thus a much stronger and earlier response to global environment change (Fu and Wen, 2002; Fu and Ye, 1995). The aridity trend is worse in semi-arid regions (Ma and Fu, 2006), for which most numerical model simulations are unsatisfactory, especially the errors of precipitation simulations, which have great uncertainties (Fu et al., 2005). Meanwhile, because the radiative effects of dust aerosols on climate in the short term cannot be ignored, considering radiative effects in a land surface model and a radiative boundary layer parameterization scheme are important problems (Bao and Lü, 2006).

In this study, enhanced observational data of dust aerosols, meteorological elements and energy fluxes near the land surface collected from the Semi-Arid Climate Observatory and Laboratory (SACOL) were used to analyze the interaction between dust aerosols and the near surface atmosphere to provide verification for numerical model results.

2 SACOL and data

SACOL, from Lanzhou University (35.57°N, 104.08°E, 1965.8 m MSL), is located in the northwest of the semi-arid region of China, where there is an annual average precipitation of 381.8 mm. The SACOL site, as a climate observation platform based on international standards, possesses advanced climate and environmental monitoring equipment and instruments as well as a well-qualified observation team, so it can conduct a variety of large-scale experimental observations. SACOL offers attractive opportunities to study certain phenomena that are believed to be important in the drought process (Huang et al., 2008).

PM_{10} (particles with aerodynamic diameter $\leqslant 10$ μm) mass concentrations were collected from an RP1400a (Thermo, USA), which continuously sampled aerosols at a height of 3.5 m with an output mass concentration every

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five minutes in units of mg m^{-3}. Meteorological elements were collected from a 35-m-high boundary layer tower, on which seven-layer wind speed (014A-L, Met One, USA), air temperature and humidity (HMP45C-L, Vaisala, Finland) sensors were installed at 1, 2, 4, 8, 12, 16, and 32 m together with a one-layer wind direction (034B-L, Met One) sensor at 8 m. The surface radiation monitoring system consists of upward and downward pyranometers (CM21, Kipp & Zonen, Holland) for outgoing and incoming short- (CG4, Kipp & Zonen) and longwave radiation that were installed at heights of 2.0 m and 3.0 m, respectively. The heat fluxes were measured at a height of 3.0 m from the eddy covariance system (EC) with a three-axis Sonic Anemometer (CSAT3, Campbell, USA) pointed toward the prevailing wind direction (LI7500, LI-COR, Campbell) (Wang et al., 2010). To ensure the consistency of data for analyses, all observation data were interpolated into the output format of 30-minute intervals.

3 Land surface factors

3.1 Observed facts and background

According to statistics from the meteorological observatory of Lanzhou, 16 dust days in 2010 were recorded on 12–14 March, 16–17 March, 19–22 March, 29–31 March, 4–5 April, 9 April, and 14 April. Figure 1 displays the daily PM_{10} concentrations at SACOL in March 2010, and the dust weather days are marked out. The dust aerosol concentration was so serious that there was no record on 19–20 March. Except for the loss on 19–20 March, the daily PM_{10} concentrations during the dust weather days were significantly higher than the other days in March, during which the most typical dust process was on 12–14 March, with values of 507.44 μg m^{-3}, 187.83 μg m^{-3}, and 52.48 μg m^{-3}, which were treated as dust storm, dust blowing, and sunny days in this paper.

According to the analysis, the center of this dust storm event was situated in front of a high-altitude shortwave trough, while the lower layer had a mesoscale circulation feature (figure omitted). There was a strong depression center at 35°N, 105°E near the front of the trough's upper layer, and the isobars and isotherms in the northwest to southeast direction were intensive, which made the cold air invade the northeast, increasing the horizontal temperature gradient, which is beneficial for frontogenesis near the surface. Therefore, the interaction of the shortwave trough at high-altitude and the mesoscale depression system resulted in an available cyclonic shear and convergence updraft, which provided impetus for the occurrence of the dust storm.

3.2 Meteorological elements

Figure 2 shows the variations of meteorological factors at SACOL from 13 to 15 March 2010, where we can see that meteorological elements had a good correlation with PM_{10} concentrations, thus providing the basis for the following diurnal variation. Figure 2a shows that wind velocity has a significant difference of level on dust storm, dust blowing, and sunny days, for which the daily mean wind speed fluctuated at approximately 5 m s^{-1}, 4 m s^{-1}, and 2 m s^{-1}, respectively. Before the dust storm, the wind velocity fluctuated approximately at the value of 5 m s^{-1} and rose sharply to 6.6 m s^{-1} at 1730 LST, and the PM_{10} concentration reached its maximum at nearly the same time. Then, the wind velocity gradually decreased accompanied by a decreasing PM_{10} concentration, except that the PM_{10} concentration changed slightly, lagging behind the wind velocity. As a result, the adjustment of wind velocity before the dust storm provided the basis for its rapid increase and better surface dust source, while the high value of wind velocity provided a good impetus for dust uplifting during the dust storm.

The daily change of air pressure was not as obvious, but it showed an increasing trend over time. On 13 March, the air pressure decreased rapidly from 800 hPa at 0000 LST to 791 hPa at 1530 LST, then increased sharply to 801 hPa at 0000 LST 14 March, after which it showed a wavelike rise until the maximum of 809 hPa. After the minimum of pressure, the PM_{10} concentration began to increase and reached its maximum three hours later. This dust storm event was under the process of decreasing pressure, indicating that low pressure was the major factor

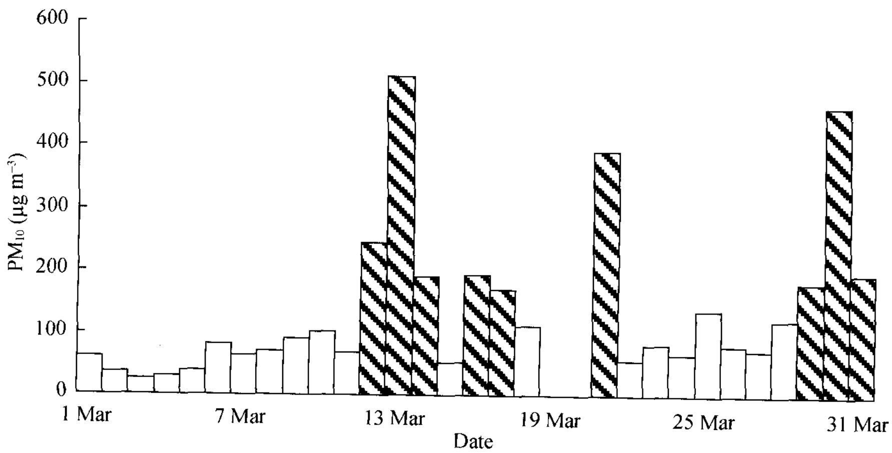

Figure 1 Daily PM_{10} concentrations at SACOL in March 2010.

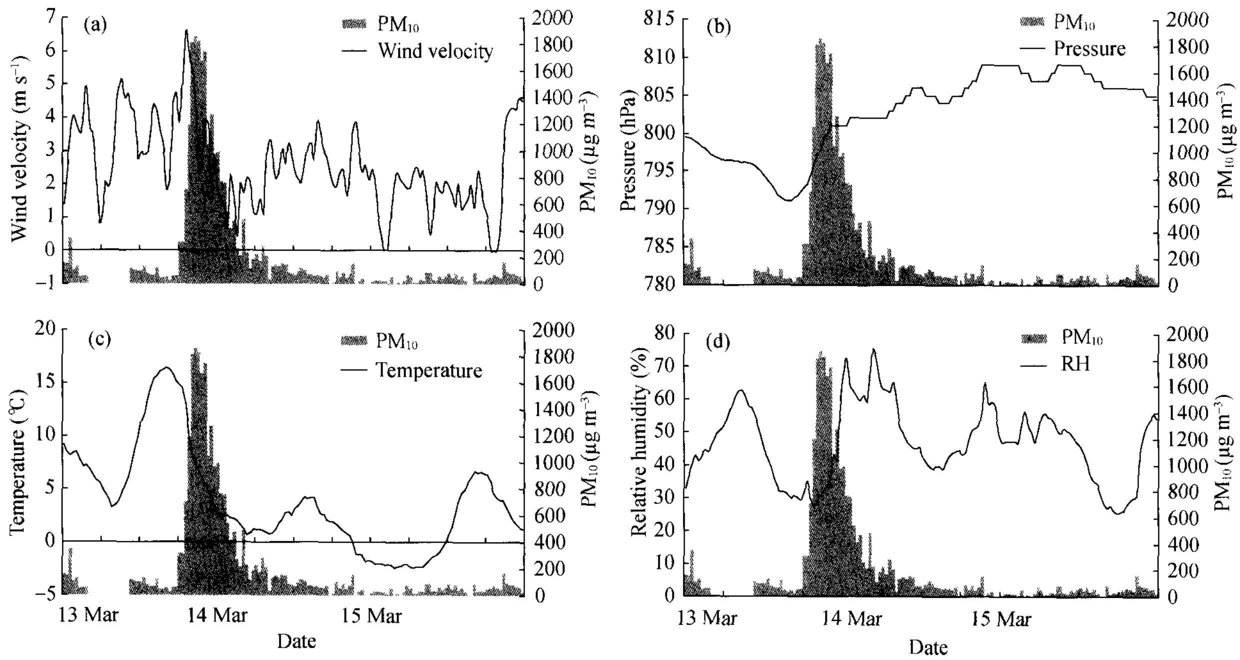

Figure 2 Variations of meteorological factors at SACOL from 13 to 15 March 2010. (a) Wind speed; (b) pressure; (c) air temperature; (d) relative humidity.

of this dust event to some extent.

Considering Figs. 2c and 2d, the air temperature and relative humidity showed an opposite change of phase, in which the air temperature had a good cyclical change. Before this dust storm, the temperature rose sharply and reached its daily maximum at 1530 LST, after which the temperature decreased gradually and dust particles were uplifted quickly into the atmosphere. Because the data of the PM_{10} concentration on the morning of 13 March was missing, the main comparison was conducted from 14 to 15 March. During that period, the dust concentration was low, and the daily air temperature changed more significantly, maintaining a high value during the dust storm events. The relative humidity responded to the dust aerosols, reaching its maximum of 63% at 0800 LST on 13 March, after which it decreased sharply to its minimum of 29% at 1700 LST. According to the statistics, during the period when the PM_{10} concentration was higher than 1000 $\mu g\ m^{-3}$, the total relative humidity was lower than 48%, while with the decrease of PM_{10} concentration, the relative humidity increased rapidly, reaching a maximum of 75%. Throughout the entire dust storm process, the atmosphere changed from cold and wet to warm and dry and then recovered to its initial state.

3.3 Radiation and heat flux

Figure 3 shows the variations of radiation and heat fluxes at SACOL from 13 to 15 March 2010. It can be seen that the energy fluxes responded to the dust aerosols later than the meteorological elements. It can be concluded that the energy factors changed more intensely on 14 March than on 13 March because the beginning of the dust storm was at approximately 1800 LST on 13 March. This result shows there were not many dust particles suspended in the air during the daytime on 13 March, while radiation and heat fluxes responded more significantly mainly in the daytime. Furthermore, after the dust storm, many fine particles were still suspended in the high level over SACOL, which would influence the energy budget of the near surface to some degree.

Figure 3a presents the diurnal variations of solar radiation, showing that downward and upward solar radiation was the typical diurnal variation of a single peak in the daytime and was almost stable at night. The downward solar radiation was significantly less during dust storm days than sunny days, and the reflected upward solar radiation decreased accordingly, the same as the land surface state. The upward and downward longwave radiation responded quite differently, as shown in Fig. 3b. The upward longwave radiation changed over time, the same as the air temperature, while the downward longwave radiation did not exhibit a significant diurnal variation and did not show much difference between day and night. One possible reason for this result is that the dust aerosols suspended in the atmosphere were continuously changing. Meanwhile, the downward longwave radiation showed a relatively flat trend of a single peak, whose maximum corresponded with the maximum of the PM_{10} concentration. With the decrease of PM_{10} concentration, downward radiation also showed a slow weakening trend. The common action of longwave and shortwave radiation is shown in Fig. 3c. It can be seen that the net radiation was less during the dust storm day than the sunny day in the daytime, while the opposite was the case at night. One possible reason for this phenomenon is that the dust aerosols suspended in the air influenced the solar radiation more significantly than the longwave radiation. During the daytime, the change of longwave radiation was covered by

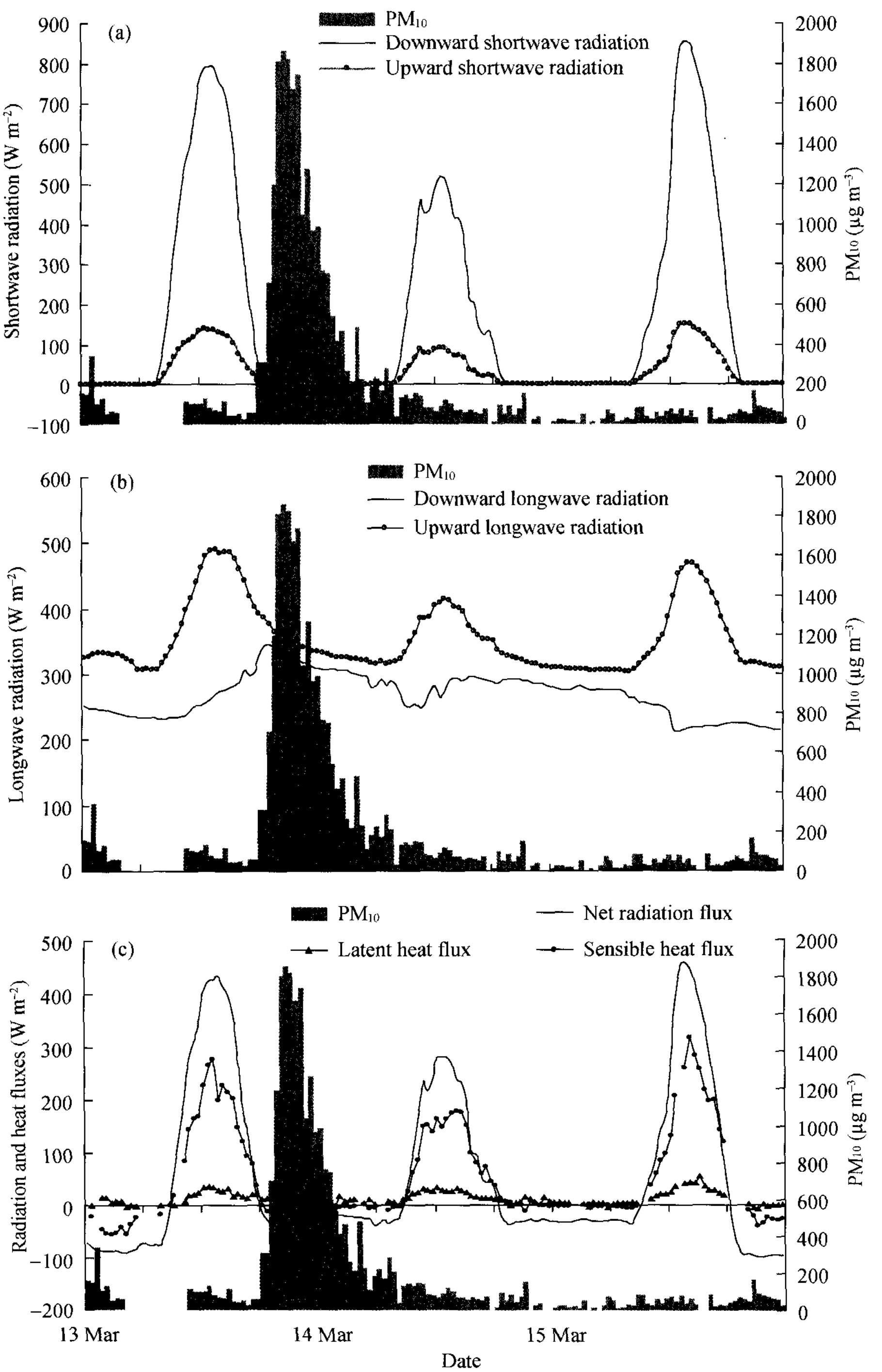

Figure 3 Variations of radiation and heat fluxes at SACOL from 13 to 15 March 2010. (a) Shortwave radiation; (b) longwave radiation; (c) net radiation and heat fluxes.

solar radiation as a result of decreasing the net radiation, while at night, the longwave radiation took the dominant position. At night, the dust particles reflected the upward longwave radiation back onto the ground as a thermal layer and emitted infrared radiation, which resulted in increased net radiation. The response of the heat fluxes decreased with net radiation, and the sensible heat flux responded more significantly. Because SACOL is situated in a semi-arid region with little annual precipitation and less of a water vapor phase transition, the variation range of latent heat flux was not as large as the sensible heat flux, only showing that the latent heat flux was slightly greater on sunny days than dust storm days. The sensible heat flux changed more intensely: during dust storm days, the sensible heat flux was significantly less than on sunny days, which indicated the decrease of energy exchange between the land surface and the atmosphere. SACOL's sensible heat flux results were contradictory to those of Tongyu station, another observation station in the semi-arid region of Northeast China. One possible reason for this discrepancy is that the dust storm event studied in this paper occurred in March of the dry season at SACOL, while it occurred in June of the rainy season in Tongyu, thus leading to the difference of near surface energy exchange. During the rainy season, the water content of the land surface was sufficient, and the sensible and latent heat fluxes nearly took the same proportion of net radiation; during dust storm days, dust particles were lifted up from the land surface, which made the soil moisture and heat capacity decrease. The result was that the temperature rose faster than the atmosphere, which meant the increase of the temperature difference and the enhancement of the sensible heat transference. In the dry season at SACOL, the sand source was sufficient, the sensible heat flux was far more than the latent heat transference, and the heat capacity of the land surface and atmosphere was so different that the dust particles suspended in the air cut the solar radiation reaching the land surface, which resulted in decreased air temperature. Furthermore, particles entering the air could also have heated the atmosphere to some extent, decreasing the difference of temperature between the land surface and the atmosphere and, accordingly, decreasing the sensible heat transference.

4 Conclusions and discussion

Enhanced observational data of dust aerosols, meteorological elements and energy factors near the land surface collected from SACOL were used to investigate the meteorological elements and dynamic factors during a typical dust storm at Lanzhou in March 2010. The results were as follows:

The whole dust storm process was controlled by high wind velocity and the decrease of pressure, and the air changed from wet and cold to warm and dry and then recovered to its initial state. The response of energy elements was slightly later than meteorological elements. During dust storm days, the net radiation was significantly higher than in sunny days in the daytime, while at night it was the opposite. Heat fluxes took the dominant position at SACOL. During dust storm days, the sensible heat flux was less than in sunny days, indicating the weakening of the heat exchange between the atmosphere and the land surface.

This paper analyzed the interaction of dust aerosols in a semi-arid region within the context of the energy budget, and it obtained meaningful results. In further studies, the inclusion of more dust examples, the remote sensing of satellite data and the quantitative analysis of the vertical distribution of dust aerosols should be the key considerations.

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