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Dust particles in the free troposphere over a Chinese desert region as revealed from balloon-borne measurements under calm weather conditions

基于静稳天气下气球探空实验的中国沙漠地区沙尘气溶胶的垂直分布

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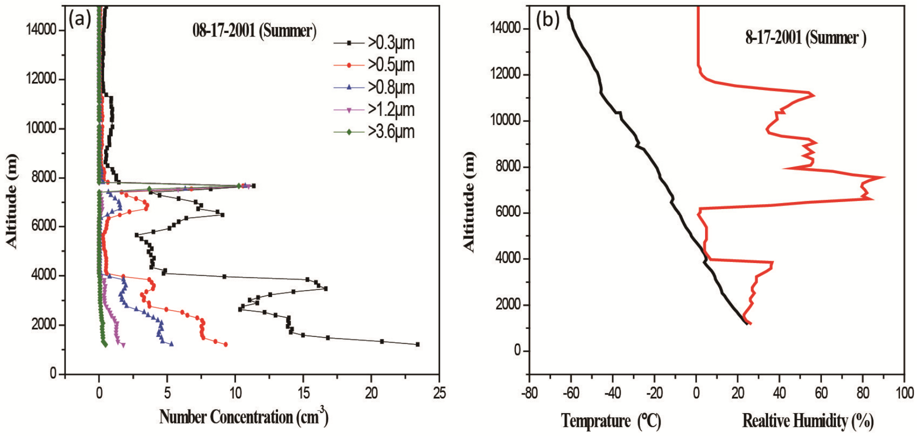
ABSTRACT

The Taklamakan Desert in China is considered to be one of the major source regions for Asian dust particles. All balloon-borne measurements in this report were carried out in Dunhuang, in the Taklamakan Desert, during calm weather conditions. The aerosol number concentration, size distribution, mass concentration, and horizontal mass flux due to westerly wind were investigated. The measurements were performed on 17 August 2001, 17 October 2001, 11 January 2002, and 30 April 2002. Five channels (0.3, 0.5, 0.8, 1.2, and 3.6 μm in diameter) were used in the Optical Particle Counter for particle size measurements. The aerosol number concentration in the winter season (11 January 2002) at 3–5 km was very high. Variation of free-tropospheric aerosols on 30 April 2002 was noticeable. A super-micron range was noticeable in the size distribution of all the measurements. Many variations in temperature and aerosol concentration were found at these inversion points. High values of estimated mass concentration of aerosols were frequently observed in the atmosphere near the ground (i.e., 1–2 km); and interestingly, relatively high concentrations were frequently detected above 2 km from the surface. Wind patterns observed using ERA-Interim data at 500 and 850 hPa showed that westerly winds dominated in the Taklamakan Desert during the balloon-borne observation period. The average horizontal mass flux of background Asian dust due to westerly wind was observed to fall within the range of 58.5–1219 tons km^{-2} d^{-1}. Vertical profiles of aerosol number concentrations showed that significant transport of aerosols dominated in the westerly region (i.e., 4–7 km).

摘要

塔克拉玛干沙漠是亚洲沙尘气溶胶的重要源地。为探讨塔克拉玛干地区沙尘气溶胶的理化特性与时空变化，研究其环境与气候效应，本文分析了四个季节在中国敦煌（塔克拉玛干沙漠内）取得的探空气球观测数据，包括气溶胶的数浓度、粒径分布、质量浓度及在西风主导下的水平输送通量。气溶胶数浓度的垂直廓线显示，来自沙漠地区的矿物粒子对局地环境与气候有重要影响，且所有季节都存在长距离输送。

粒子谱分布显示局地有大量粗粒子输入。结果说明，源于塔克拉玛干沙漠的沙尘气溶胶的背景输送有着重要的科学意义，需进一步研究其对东亚和西太平洋地区环境与气候的影响。



1. Introduction

One of the significant components of the earth–atmosphere system is aerosols. Atmospheric aerosols originate from natural and anthropogenic activities (Zhang et al. 2010). The effects of aerosols are closely associated with their physical characteristics, size, surface albedo, and aerosol layers at different altitudes (Mahowald et al. 2010). Northern and western China are among the world's largest natural dust aerosol regions(Chen et al. 2015). Chinese desert regions e.g., the Taklamakan Desert in West China, or the Gobi Desert in Mongolia and Northwest China, are considered to be the major dust source regions in Asia. Asian dust is transported eastward towards Korea, Japan, and sometimes the Pacific Ocean (Sun et al. 2010).

The Taklamakan Desert, one of the major sources of background Asian dust, is situated in the Tarim Basin, with the Tianshan Mountains in the north, Pamir Plateau in the west, and Kunlun Mountains in the south (Huang et al. 2008). Uno et al. (2001) found that Asian dust particles from the Taklamakan Desert are transported over a long range compared those from the Gobi Deseret.

The area is considered effective for analyzing desert aerosols transported over a long range, which in this region is mainly influenced by westerly winds. Dunhuang (40°00′N, 94°30′E, 1146 m a.s.l.) is located in the east of the Taklamakan Desert, China (Figure S1). The area is significant for studying the initial state of Asian dust particle transportation. For this reason, Dunhuang was selected as the observational site in this study.

The aim of this this study was to analyze the dust-aerosol characteristics in the Taklamakan Desert area, such as the number concentration, size distribution, mass concentration, and mass flux, under calm weather conditions. The findings of the study should help future investigations of Asian dust-aerosol characteristics, their possible impact on regional weather and climate activities and the vertical profile of aerosol, as well as the variation in weather parameters on certain days under calm conditions.

2. Data and methods

2.1. Balloon-borne measurements of aerosol number concentration

A balloon train was used to measure the aerosol number concentration and size on 17 August 2001, 17 October 2001, 11 January 2002, and 30 April 2002, with an Optical Particle Counter (OPC) over the free troposphere under calm weather conditions at Dunhuang. This balloon-borne particle counter used in sampling has been described in many studies (Hayashi et al. 1998). The main specifications of the balloon-borne particle counter are described in Table S1. To measure the particle number concentration and size, the forward scattering effect was used. The OPC's light source was a semiconductor laser, and a photodiode was used for the detection of light scattering from aerosols. The signals from the detector with radio waves 400 MHz in wavelength transmitted the information to the balloon launching site. The optical counter used in the balloon-borne measurements consisted of five channels (0.3, 0.5, 0.8, 1.2, and 3.6 μm in diameter). Balloon positioning during the balloon flight was monitored using GPS. Wind speed was calculated based on balloon trajectories, while a meteorological radiosonde (Vaisala Co. Ltd, (Japan) was mounted on the balloon to monitor the atmospheric temperature and relative humidity signals. A maximum height of 15 km above the ground was taken as covering the free troposphere's vertical distribution.

2.2 Size distribution of aerosols

A lognormal distribution function was computed for the size distribution of aerosols. A zero-order lognormal size distribution function (ZOLD) was applied as fitting functions to the measurements by Deshler, Johnson, and Rozier (1993). The function is defined by the following equation:

$$N(D) = A_{\mathrm{exp}}\ [[-\mathrm{In}^2\ (D/D_{\mathrm{m}})]\ /\ [2\mathrm{In}^2\sigma]],$$

where D is the particle diameter, D_{m} is the mean diameter, and σ is the standard deviation, In^2 is the integral of exponential function, and A_{exp} *is* exponent of the surface area of particle.

We first estimated the ZOLD function by fitting the data with lognormal size distributions (bimodal distribution), and then this ZOLD function was compared with the observed data from the balloon-borne measurements to fix other functions.

2.3 Estimation of the mass flux of aerosols

The horizontal mass flux of desert aerosols was estimated using the following procedure described by (Iwasaka et al. 2008), on the basis of size and number concentrations of aerosols in the Taklamakan Desert region of China. Okada et al. (2001) assumed that coarse-mode particles are oval in shape, with a long axis *a* and short axis *b*. Thus, we estimated the volume concentration V_j to verify quantitatively that coarse particles are foremost in the volume concentration of particulate matter in altitude layer *j*, as described by the following:

$$V_j = (\tfrac{4}{3})\pi \sum_i a_i b_i^2 n\left(r^i\right)_j, \tag{1}$$

where r^i is the geometric mean radius of the *i*th size bin, and $n(r^i)_j$ = the number concentration of aerosols in altitude layer *j*. The values of *a* and *b* in the given relation are (Okada et al. 2001):

$$a_i \times b_i = r_i. \tag{2}$$

The mineral dust density of 2.6 g cm^{-3}, calculated by Ishizaka and Uno (1982) for desert aerosols, was used. By multiplying this density by the volume concentration at layer *j*, we can calculate the mass concentrations of aerosols M_j (g cm^{-3}) at layer *j*:

$$M_j = V_j \times \rho, \tag{3}$$

where ρ is the mineral dust density. From the wind speed and direction at layer *j*, we estimated the mass flux over the Taklamakan Desert area (F_j) from the following relation:

$$F_j = M_j \times \mathrm{Wind}_j. \tag{4}$$

2.4 The Hybrid Single Particle Lagrangian Integrated Trajectory model

The Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT) is a simple and useful tool for studying the sources of aerosols and transport pathways of air masses (Stein et al. 2015) . The meteorological input for HYSPLIT is from the National Centers for Environmental Prediction–National Center for Atmospheric Research, based on global reanalysis meteorological data (http://ready.arl.noaa. gov/gbl_reanalysis.php). The total air mass back trajectories corresponding to the balloon-borne measurement dates for 72 h were computed for the observational site at different altitudes of 1000 m , 1500 m, and 3000 m above ground level.

3. Results and discussion

3.1 Balloon-borne measurements of aerosol number concentrations

Table S2 shows the balloon launch times and weather conditions on observation days. Figure 1a and b and Figure S2a–f show the vertical distribution of aerosol number concentration, humidity, and temperature profiles in the Dunhuang desert region on 17 August 2001, 17 October 2001, 11 January 2002, and 30 April 2002. The aerosol number concentrations were compared with the temperature and relative humidity profiles.

The aerosol concentrations shown in Figures 1 and S2 are the distributions averaged with a running mean at height intervals of 700 m to avoid small variations that may occur due to the dynamic motion of air. It was observed that the weather was not clear on two observation days, i.e., 17 August 2001 and 30 April 2002, and measurements were taken after light rain. Weather conditions were stable on 17 October 2001 and 11 January 2002.

In the relative humidity profile of 17 August 2001 (Figure 1b), high humidity was observed in the 6–8-km region. Enhancement in the number concentrations of aerosols in this region (i.e., 6–8 km; Figure 1a) corresponded well to the humidity profile. Sharp peaks in aerosol number concentrations were observed in the 7–8-km region because of thin clouds; the concentration of particles having a diameter of 0.3 μm was comparable to that of particles with a diameter of 3.6 μm. Number concentrations of aerosols were high near the ground on 17 October 2001 (Figure S2c), as compared to other seasonal measurements. This may have been due to stable atmospheric conditions. The vertical profiles of aerosol number concentrations were complex on 30 April 2002 (Figure S2f) because the balloon was launched just after rain. In the mid-troposphere, high-humidity layers and a dry atmosphere were also found in the measurements of 17 August 2001, 17 October 2001, and 11 January 2002, suggesting that air masses have different features, possibly related to the nature of dust particles in different layers of the atmosphere. The results show that, in this study region, the mixing-height layer for aerosol number concentrations is 6–8 km in summer, possibly due to adiabatic expansion and high temperatures, and 4–5 km in other seasons. The number concentrations of aerosols decrease with an increase in altitude in all seasons, but several peaks can be found in the 6–8-km region. This suggests that aerosol concentration profiles are greatly affected by the dynamic movement of air.

In all seasons, aerosols usually found between 5 and 8 km regions above the ground were transported by horizontal wind movement, which agrees well with the results of (Huang et al. 2008). Although, according to the OPC results, the Taklamakan Desert's free troposphere is likely to be dustier in spring than in summer—a finding supported by routine meteorological reports demonstrating the occurrence of dust episodes in the Taklamakan Desert to be higher in the spring than the summer season. The vertical distribution of dust was investigated from Lidar observations in April 2002, and strong diurnal variations in the dust layer were reported during dust storm events (Hussein et al. 2006; Iwasaka et al. 2004).

3.2 ZOLD number size distribution

In Figure 2a–d, the curves show the size distributions of dust particles found in the troposphere deduced from the aerosol number concentration measurements of Figures 1 and S2. The expected ZOLD functions were compared with number size distributions observed at Dunhuang. The ZOLD function parameters are summarized in Table 1.

The mean diameter of aerosols from observed data ranged from 0.02–0.3 μm for fine-mode particles, while for coarse-mode particles it was 0.8–1.2 μm. In the free troposphere, the number size distribution pattern showed a peak of super-micron size range ($d > 1$ μm), suggesting a contribution by mineral particles near the ground surface. A super-micron range was noticeable in the measurements of 30 April 2002, suggesting mineral dust particles were strong sources from the ground surface. The size of dust particles in spring was found to be larger than in other seasons. It was observed that the size distribution in Dunhuang near the ground surface was super-micron in range. This suggests that mineral particles were significant super-micron particles in the atmosphere, added via aerosol transportation from the Asian desert region.

Figure S3a–d shows the size distribution patterns in the lower troposphere in all four measurements. A difference in particle size was found in all layers of the free troposphere. On 17 August 2001 (Figure S3a), no clear peaks of super-micron size range were observed in the 4–8-km region. Super-micron size-range peaks were, however, observed frequently in the measurements of 17 October 2001 and 30 April 2002 (Figure S2b and d). There was no super-micron size range found on 11 January 2002 (Figure S2c) in the 4–8-km region. Super-micron size-range peaks were also reported by Kim et al. (2003), who investigated balloon-borne measurements over a desert region in Asia. The number concentrations of particles in different layers of the troposphere are controlled not only by aerosol transportation, but also by various microphysical processes (evaporation, condensation etc.). Moreover, the enhancement of super-micron particle concentration has been reported in the boundary layer of the atmosphere (Iwasaka et al. 2003). Balloon-borne measurements performed at Yulin for the vertical distribution of tropospheric-aerosol number concentrations and size distributions showed that fine-mode particles were strongly present in the troposphere, while in the stratosphere coarse-mode particles were the major component of all atmospheric aerosols (Xu et al. 2004).

3.3 Mass concentration and horizontal mass flux of desert aerosols estimated from balloon-borne measurements

The mass concentrations of desert aerosols, calculated on the basis of Equations (1), (2), and (3), are shown in Figure 3a. High values of mass concentration near the ground (1–2 km) were detected in all seasons. In most observations, high values of mass concentrations were also detected above 2 km. In the westerly region (4–7 km), high values were found in spring. The values of mass concentration decreased above 6 km, where aerosols are removed rapidly in the westerly region due to strong wind speeds (> 5 km h^{-1}). The mass concentration of dust particles was 50 μg m^{-3} or higher in the westerly region (4–7 km) during calm weather conditions. Concerning the mass distribution of dust particles from aircraft measurements in Japan, the dust particle load at 2–3 km was 2.3–2.6 μg m^{-3}, suggesting the long-range transport of dust particles in calm weather (Trochkine et al. 2003).

Figure 3b shows the vertical distribution of the horizontal mass flux of desert aerosols. The horizontal mass flux was estimated form Equations (1) to (4). A high value of horizontal mass flux was found on 17 October 2001 near the ground (474 tons km^{-2} d^{-1}), whereas there was a lower value on 11 January 2002 (1.39 tons km^{-2} d^{-1}). During long-range transport, various dilution and deposition processes occur, so the difference in values between the ground level and upper troposphere may suggest those processes according to different seasons (Iwasaka et al. 2008). Flux values decreased above the westerly region. The flux values were low due to stable weather conditions, as the vertical mixing of aerosols decreases and the supply of aerosols above 5 km is suppressed under calm weather conditions. High levels of horizontal dust flux were found during daytime at Tazhong (in the hinterland of the Taklamakan Desert), with an annual total flux of 3903.2 kg for a 100 × 200 cm section (Yang et al. 2013)

4. Wind pattern over the Taklamakan Desert during the balloon-borne observation period

Figure 4 illustrates the backward trajectories of air masses for three days, provided by NOAA, from which we can examine the history of air masses on the balloon observation dates at heights of 1, 3, and 6 km a.s.l. Air masses were strongly affected by westerly winds from the Taklamakan Desert at 3 and 6 km on 17 August 2011, 17 October 2011, and 11 January 2002; whereas, the air masses at 3 km and 6 km from the northern part of the Tianshan Mountains and from the Taklamakan Desert on 30 April 2002 converged around the southwestern part and reached Dunhuang. The air masses from the north around Dunhuang are usually blocked by high mountains (the Qilian Mountains). Significant aerosol number concentrations were also found in the westerly regions (5–8 km), demonstrating the long-range transport of Asian dust particles by westerlies from the Taklamakan Desert, in agreement with Iwasaka et al. (2008). In Dunhuang, winds from the north side are usually blocked by the high Qilian Mountains and turn westwards due to the geography of the Tarim Basin. The vertical distribution of dust involved the transport of dust particles upward with dynamic force from the mixed layer to the free troposphere. Westerlies carried these dust particles over long distances (Yamada et al. 2005).

Figure S4 shows the wind vectors at 500 hPa (4 km) and 850 hPa (1.1 km) on 17 August 2001, 17 October 2011, 11 January 2002, and 30 April 2002 at Dunhuang during the balloon-borne observation period. ERA-Interim data at a resolution of 0.75° were used to deduce the wind pattern.

The air masses from the Tianshan Mountains (north) in the Tarim Basin at 500 hPa and from the east reached Dunhuang at 850 hPa on 17 August 2001, which then converged towards the western part (Figure S5a). This agrees with the wind pattern reported by Sun, Zhang, and Liu (2001). Westerly winds dominated over the Tarim Basin in the Taklamakan Desert in the upper-level chart of 500 hPa on 17 October 2001, 11 January 2002, and 30 April 2002 (Figure S4c, e, and g). Winds on 30 April 2002 were developed on the Tianshan Mountains with northerly flow at 850 hPa, and spread over the whole Tarim Basin with a dominating easterly component. These results show good correspondence to the report by Seino et al. (2005), and suggested the origin of new wind flow that increased the dust emissions from different areas in the Tarim Basin. The Taklamakan Desert is surrounded by high mountains on the north, west, and south edges (i.e., 5000–7000 m high), and therefore the dust particles at lower altitude (5000 m) cannot easily move outside from this desert area (Zu et al. 2008). The direction of the transportation of air masses in summer was through the Tianshan Mountains from the north towards the Dunhuang desert region, which caused the transportation of aerosols to the northeastern region and the Pacific Ocean. The major reason for this was the high heating rate of the boundary layer in the atmosphere caused by convection in summer.

5. Conclusions

The balloon-borne measurements made at Dunhuang in 2001 and 2002 and analyzed in this paper led us to the following conclusions with respect to altitude and seasonality. Firstly, coarse particle sizes can be frequently observed in the mid and lower troposphere. The vertical profiles of aerosol number concentrations strongly suggest that mineral particles originating from desert areas have an influence locally and are transported long distances in all seasons. The vertical distribution of particle concentrations with aerosols larger than 3.6 μm in diameter exhibited a decrease in concentration at the altitude of 5–10 km a.s.l. The size distribution function of particles indicated enhancement of particles with coarse-mode particles. High values of particle mass concentrations were frequently observed in the ground layer (1–2 km) and, interestingly, relatively high concentrations were frequently detected above 2 km. The horizontal mass flux of dust particles by westerly winds was very large in the free troposphere, and it was believed that the large amounts of dust particles were transported by westerlies to downward regions. The results suggest that background Asian dust transported from the Taklamakan Desert is important to study, and more investigations are required to clarify the effect of this dust on the environment and climate of East Asia and western Pacific regions.

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Table 1. Parameters of ZOLD distribution.

Date	Mode	Mean diameter (µm)	Standard deviation
17 August 2001	Fine	0.028	2.6
	Coarse	0.8	2.1
17 October 2001	Fine	0.028	2.6
	Coarse	0.89	2.1
11 January 2002	Fine	0.3	2.99
	Coarse	0.8	2.1
30 April 2002	Fine	0.1	2.9
	Coarse	1.22	1.8

Figure 1. The (a) aerosol number concentrations (0.3 μm, 0.5 μm, 0.8 μm, 1.2 μm, 3.6 μm) and (b) atmospheric temperature (black line) and relative humidity (red line) in the troposphere on 17 August 2001 at Dunhuang, China.

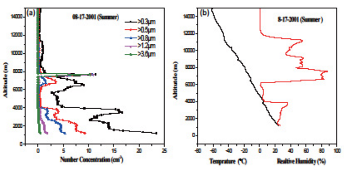


Figure 2. ZOLD-type number size distribution function and observed number size distribution patterns.

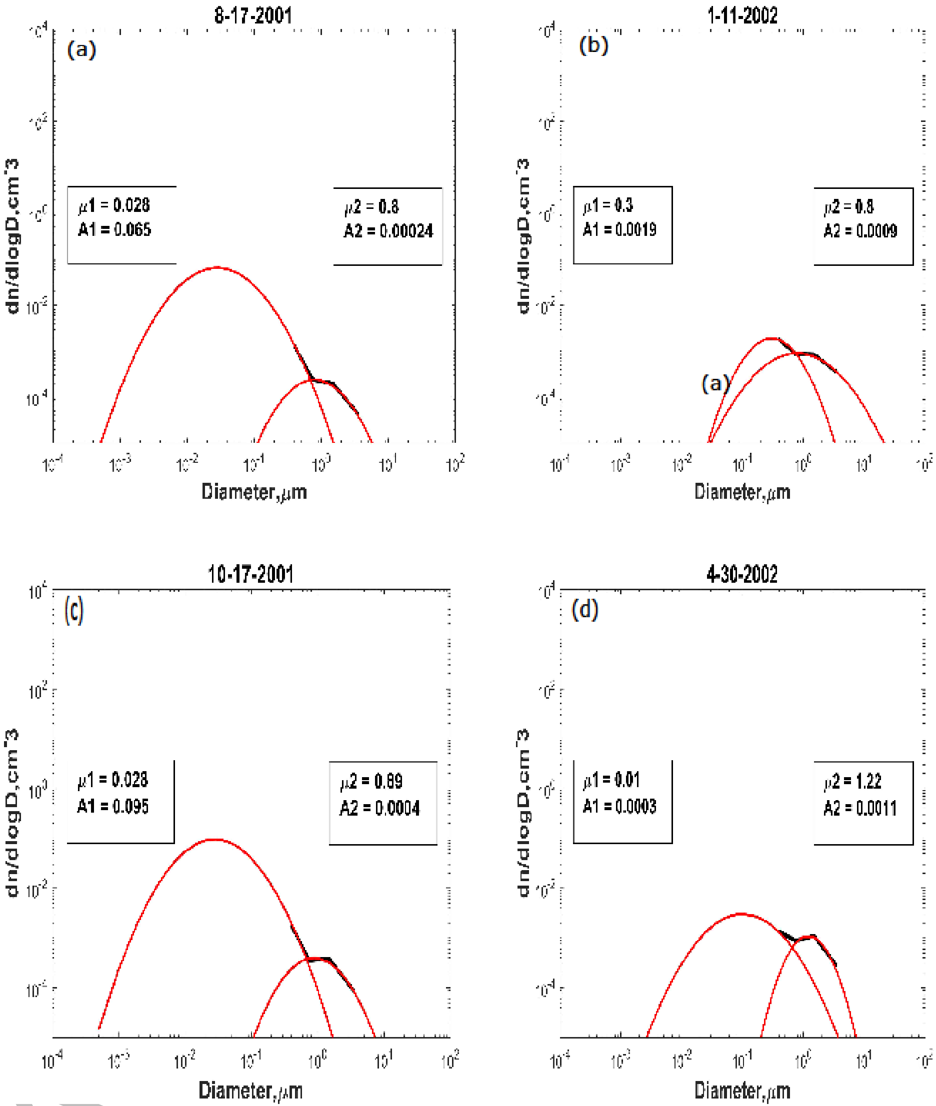


Figure 3. Vertical profiles of estimated (a) mass concentration (units: μg m^{-3}) and (b) horizontal mass flux (units: tons km^{-2} d^{-1}) on 17 August 2001, 17 October 2011, 11 January 2002, and 30 April 2002 at Dunhuang, China.

Comment [lxc1]: Please size Fig.3 at single column width (8 cm).

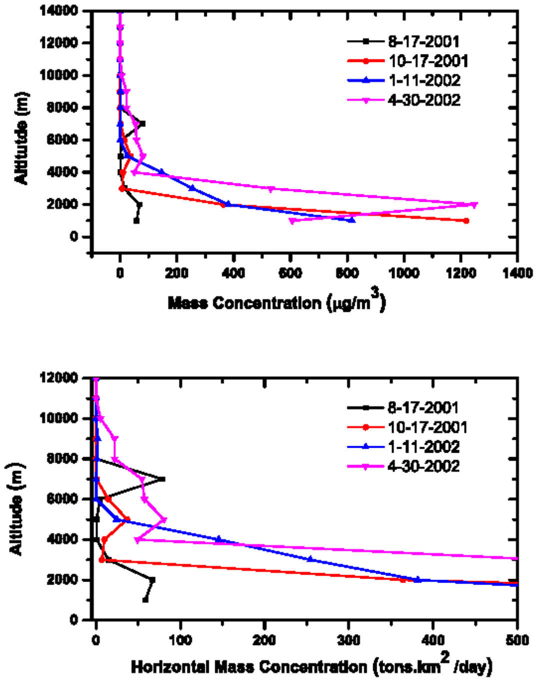
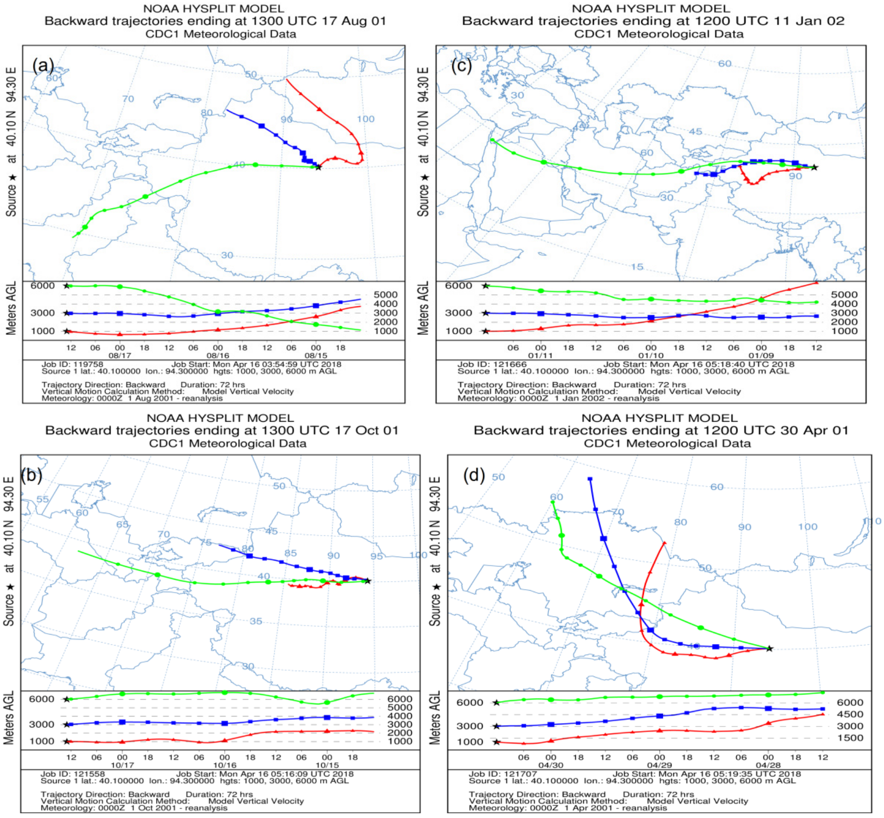


Figure 4. Backward trajectories of air masses at heights of 1 km, 3 km, and 6 km observed on (a) 17 August 2001, (b) 17 October 2011, (c) 11 January 2002, and (d) 30 April 2002 at Dunhuang, China.



Online Supplemental Material

Dust particles in the free troposphere over a Chinese desert region as revealed from balloon-borne measurements under calm weather conditions

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This file includes:

Supplementary Figures S1–S4 and Tables S1–S2

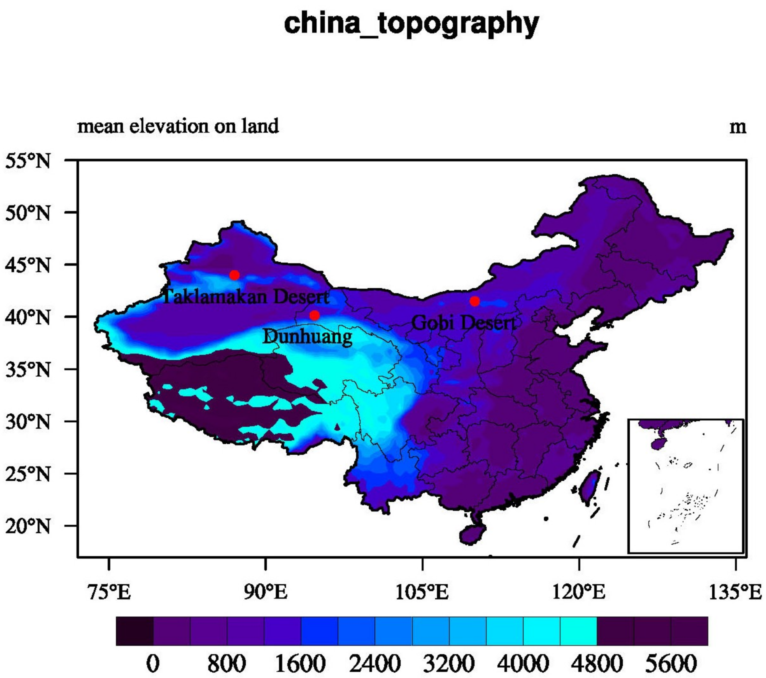

Figure S1. Observational site at Dunhuang, near the western edge of the Taklamakan Desert, China.

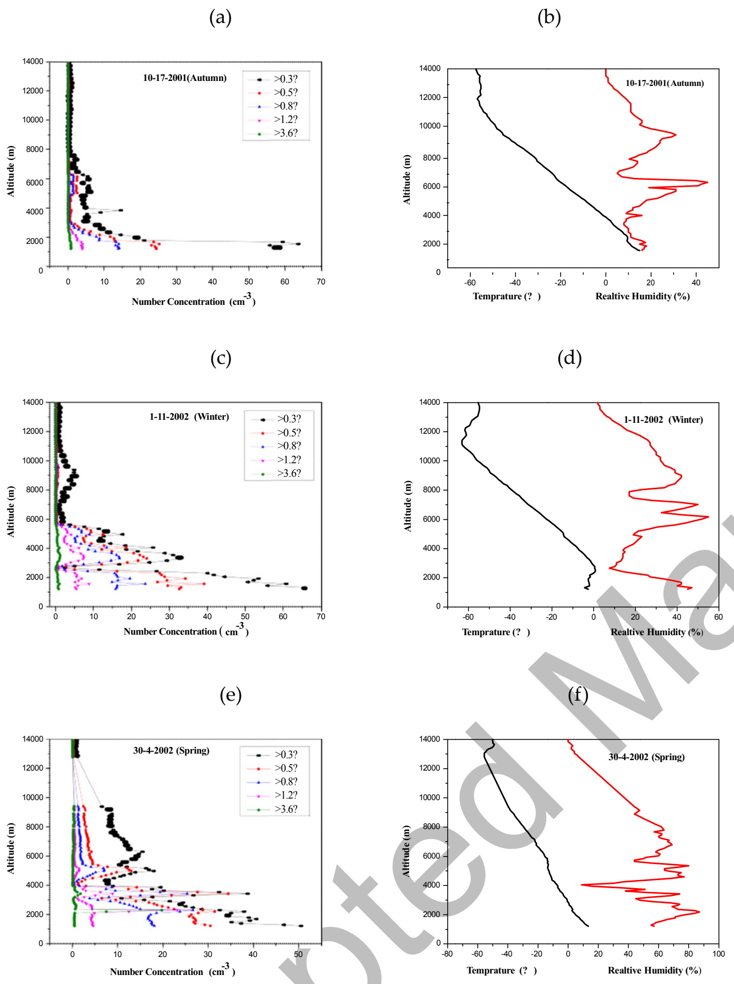

Figure S2. The (a, c, e) aerosol number concentrations (0.3 µm, 0.5 µm, 0.8 µm, 1.2 µm, 3.6 µm) and (b, d, f) atmospheric temperature (black line) and relative humidity (red line) in the troposphere observed on (a, b) 17 October 2011, (c, d) 11 January 2002, and (e, f) 30 April 2002 at Dunhuang, China.

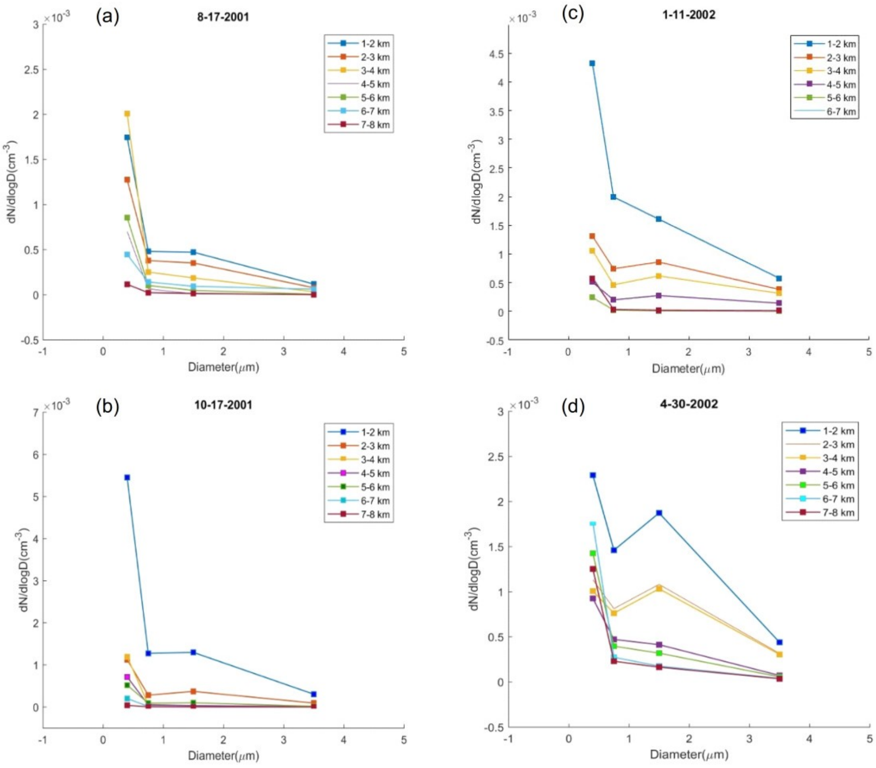

Figure S3. Size distribution patterns of dust particles measured in the free troposphere on (a) 17 August 2001, (b) 17 October 2001, (c) 11 January 2002, and (d) 30 April 2002 at Dunhuang, China.

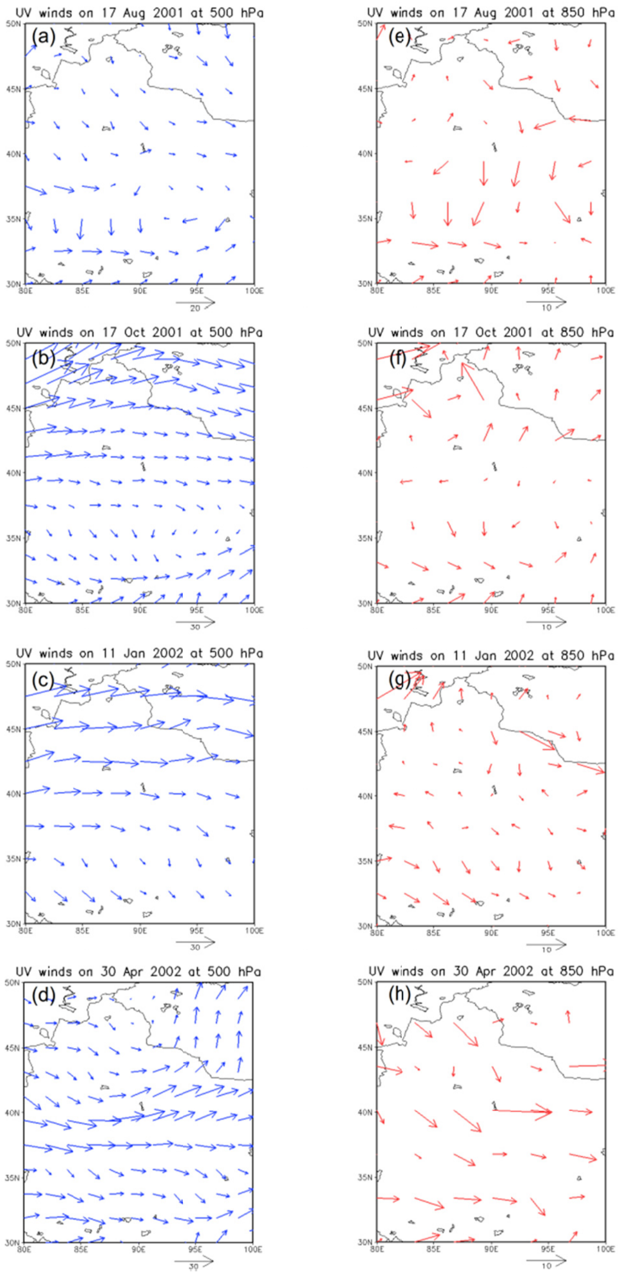

Figure S4. Patterns of air masses at 500 hPa and 850 hPa on (a) 17 August 2001, (b) 17 October 2001, (c) 11 January 2002, and (d) 30 April 2002 over Dunhuang and the Taklamakan Desert region, China.

Table S1. Balloon-borne OPC specification.

Balloon-borne OPC parameters	Specifications
Volume	30 × 35 × 35 cm
Weight	5.5 kg (including battery)
Operation time	6 h
Detection	Forward scattering light detection 13°–44° from the laser beam axis
Detector of scattering light	Photodiode
Light source	Laser diode; wavelength = 810 nm
Sampling time interval	20 seconds per measurement
Frequency of radio wave for data transmittance	400 MHz (Vaisala radiosonde)

Table S2. Balloon launch times (local time), dates, and weather conditions of the observational period.

Date	Balloon launching time	Weather conditions
17 August 2001	1315	Fine but very thin clouds, northeast wind near surface and below 3 km, wind speed at 1.5 km of 14 m s^{-1}
17 October 2001	1130	Weak wind, clear, no cloud, low temperature, calm weather conditions, and strong northwest wind above 1 km
11 January 2002	1200	No cloud, no wind, visibility of 15 km, weather conditions calm, thick inversion layer from surface to 2.5 km, southwest wind
30 April 2002	1200	Just after drizzle, visibility of 30 km, fully cloudy, westward surface wind, southeast wind above 5 km, thin

	inversion layer form surface to 400 m