Chapter 9
Mass Transport of Background Asian Dust Revealed by Balloon-Borne Measurement: Dust Particles Transported during Calm Periods by Westerly from Taklamakan Desert

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Abstract The dust storm which is caused by low pressure activities in China and Mongolia has been investigated by many investigators, but very thin dust clouds, which can be frequently detected in every season (we call it background Asian dust here) by lidar in Japan, Korea, and China but not by satellite, have attracted very few investigators since detection of the cloud is not easy. It, however, has been suggested that the background Asian dust also plays an important role in the biogeochemical cycle of dust in east Asia and west Pacific regions through long range transport of dust particles by westerly winds, and information of outflow rate of background dust particles over the dust source areas is strongly desired since previous investigations were made mostly in the down wind regions (Iwasaka et al. 1988; Matsuki et al. 2002; Trochkine et al. 2002). According to the balloon-borne measurements made under the calm weather condition in 2001–2004 at Dunhuang (40°00′N, 94°30′E), China, mass flux of background Asian dust due to westerly wind was about 50 ton/km^2/day over the Taklamakan desert (about 4 to 6 km altitudes) and

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total mass of mineral dust transported by westerly from the Taklamakan desert to downwind will be about 1.4 × 10^7 ton/year. From those values it is suggested that background Asian dust transported from the Taklamakan desert is very important and more investigations are desired to clarify the effect of the background Asian dust to environment and climate in east Asia and west Pacific regions.

Keywords: Background Asian dust, background KOSA, balloon-borne measurement, mass flux of Asian dust particle

9.1 Introduction

Asian dust layers with the peak height of about 4–6 km and layer thickness of about 0.5–2 km were frequently detected in Japan, Korea, and China by lidar (e.g., Iwasaka et al. 1988; Kwon et al. 1997; Sakai et al. 2000; Murayama et al. 2001). Those Asian dust events have been called background KOSA (or weak KOSA) since meteorological observatories give no report of dust and few typical dust storms are identified in arid and/or semi-arid regions of China and Mongolia. Additionally it is hardly possible to detect such types of dust events through satellite imaging.

Recently aircraft-borne measurements were made to understand the nature of background KOSA (Mori et al. 1999; Trochkine et al. 2002; Matsuki et al. 2002, 2003) since it is hardly possible, from lidar measurements, to know the mixing state of KOSA particles and other types of aerosols such as sea salt, sulfate particles and others, and consequently we cannot estimate mass concentration and/or mass flux of background KOSA.

It has been believed for a long time that the effect of the Asian continental air becomes extremely small in Japan, Korea, and east coast of China in summer since the global air-circulation pattern and land surface vegetation largely change in summer in the Asian-Pacific region. However, this is speculative since there have been few observations of long-range transport of atmospheric constituents in the free troposphere owing to technical difficulty. Matsuki et al. (2003) suggested that the effect of Pacific high is very strong below about 4 km over Japan islands but not above about 4-km altitude even in summer, and that major particles were mineral dust particles in coarse mode above about 4 km even in summer since westerly winds actively transports atmospheric constituents including KOSA particles in the free troposphere.

Iwasaka et al. (2004) suggested, on the basis of lidar measurements made at Dunhuang, China, the Taklamakan desert as a possible pool which can flow out Asian background dust in every season. Both mountain-valley winds and westerly above about 5 km were suggested as important system transporting background Asian dust from the Taklamakan desert to down wind (Iwasaka et al. 2003b and 2004). However it is hardly possible, as mentioned above, to estimate quantitatively outflow rate or mass flux of dust particles from their lidar measurements.

In 2004, balloon-borne measurements have been made, following the balloon and lidar measurements in 2001–2003, at Dunhuang (40°00′ N, 94°30′ E), China to understand the mass flux of dust particles supplied in to the atmosphere from the Taklamakan desert under calm weather conditions. The observations showed that lots of dust particles diffused up to the free troposphere (~5 km) and were transported out by westerly over the Taklamakan desert (here we called it Asian background dust and distinguish it from the Asian dust caused by cyclone in the Asian continent). Here we showed how to measure and to estimate the mass of background Asian dust and discussed possible importance of contribution of background dust in mass budget in Asia-Pacific regions.

9.2 Mass Flux of Dust Due to Westerly over Taklamakan Desert

9.2.1 Balloon-Borne OPC to Measure Aerosol Size and Concentration

Figure 9.1 shows the balloon train (configuration of instruments) to measure aerosol size and number concentration with balloon-borne optical particle counter (OPC). The detailed specification of the balloon-borne OPC was described already (e.g., Hayashi et al. 1998) and we shortly described the outline of it here. We used the forward scattering effect of particles to measure particle size and number concentration, and the OPC contained semi-conductor laser as light source and photodiode as detector of scattering light from the aerosols. The

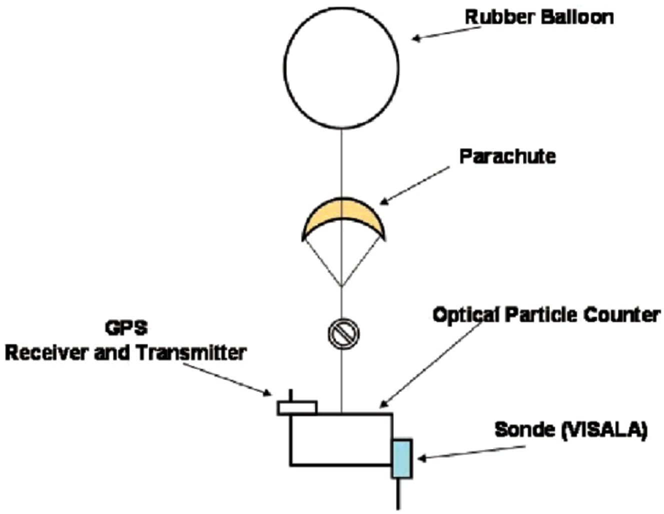

Fig. 9.1 Balloon train to measure aerosol number concentration and size by balloon-borne optical particle counter

output signals from the detector were transferred by radio wave with wavelength of 400 MHz. Particle sizing was made at particle diameters of 0.3, 0.5, 0.8, 1.2 and 3.6 μm, and modified those to diameters of 0.3, 0.5, 0.8, 1.2, 2.0, 3.0, 5.0 and 7.0 μm in measurements on October 24, 2004 to obtain more detailed number-size distributions.

9.2.2 Observation of Wind Speed and Direction

The receiving antenna of GPS (geographical positioning system) signal and transmitter which transfers the signal to the balloon launching site was mounted on the balloon to monitor the balloon position during the flight of the balloon. Wind speeds and directions were estimated from analysis of the balloon trajectories.

9.2.3 Atmospheric Temperature and Humidity

Atmospheric temperature and humidity were monitored by meteorological radio sonde of VISALA Co. Ltd. and those signals also were transferred by radio with wavelength of 400 MHz. The humidity sensor, according to VISALA Go. Ltd., can not work properly under the atmospheric temperatures lower than 213 K (−60°C), and therefore the values of relative humidity shown in Fig. 9.2 have some uncertainties above 13 km.

9.2.4 Measurements Under Calm Weather Condition

The balloon-borne measurements were made under the calm weather conditions; wind speeds lower than 2 m/s near the ground and cloudiness lower than 1/8, and therefore the observed results can be recognized as ones showing background levels. The local meteorological observatory gave no reports of dust storm. Figure. 9.2 shows aerosol number and size distributions, atmospheric temperatures, and wind speeds over Dunhuang (40°00′ N, 94°30′ E), China on January 11, 2002; August 27, 2002; February 24, 2003; March 24, 2003 and October 24, 2004.

The particle concentrations were high near the ground and gradually decreased according to increase of height, but many peaks of aerosol layer were identified and corresponded well to temperature inversion and humidity changes. Roughly speaking the coarse particles with their radius larger than 1.2 μm seem to be well mixed from near the boundary to about 5 km and westerly wind dominated above about 5 km. Those features are found also in the measurements made on other days (August 17,

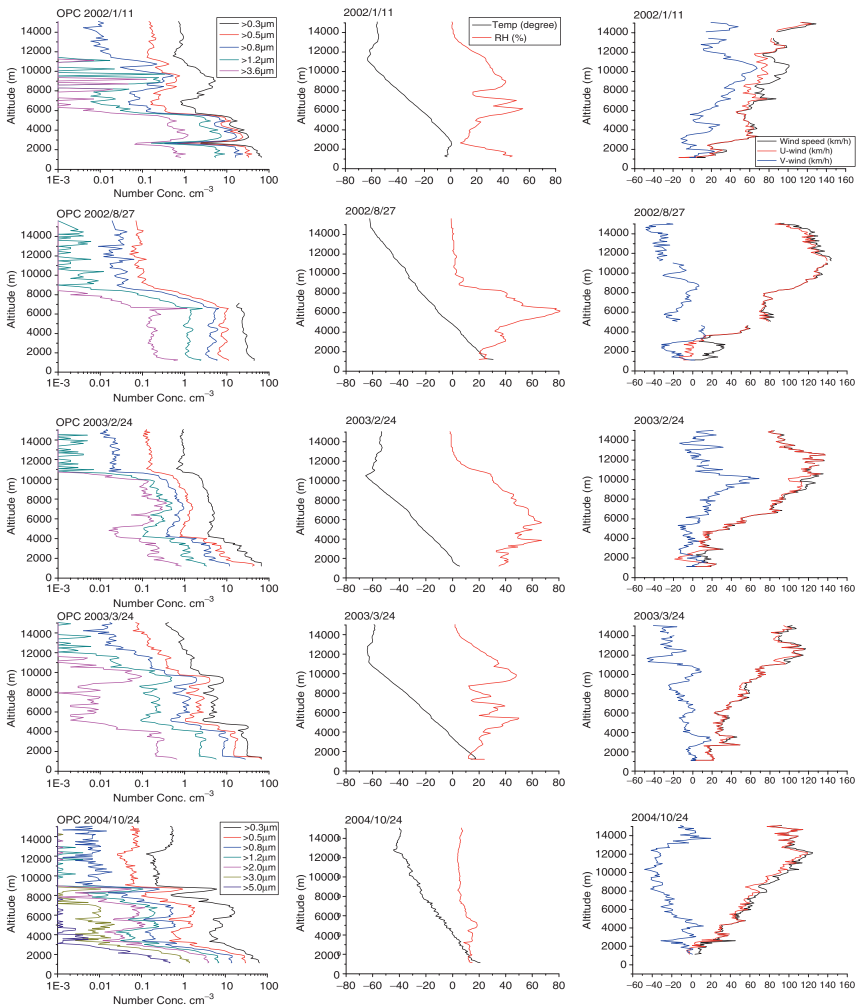

Fig. 9.2 Vertical profile of number-size distribution (cm^{-3}), Atmospheric temperature (°C), Relative Humidity (%), Wind speed (km/h), U-wind speed (km/h) and V-wind speed (km/h) on January 11, 2002, August 27, 2002, February 24, 2003, March 24, 2003 and October 24, 2004. U-wind represent the longitudinal components of wind, positive values in U-wind indicate westerly flows. V-wind represent the latitudinal components of wind, positive values in V-wind indicate northerly flows

2001; October 17, 2001; April 30, 2002; and March 22, 2004, those measurements were made without GPS signal detection and are not shown here and available to see in Kim et al. 2003 and Iwasaka et al. 2003b)

The wind, here, is divided to two components: U-wind and V-wind. U-wind and V-wind refer to the longitudinal component (positive values indicate westerly) and latitudinal component (positive values indicate northerly flows) of winds, respectively.

9.3 Mass Flux of Background Asian Dust Transported by Westerly over Taklamakan Desert

Iwasaka et al. (2003a) and Yamada et al. (2005), on the basis of chemical element analysis and observation of morphology of the particles collected with the balloon-borne impactor during the campaign of balloon-borne measurements made at Dunhuang, China corresponding to the balloon-borne OPC measurements, showed that dust particles dominated in the coarse mode size in the free troposphere over the Taklamakan desert (for example; 86% in August 29, 2002 and 99% in March 24, 2003). Therefore we, according to the analytical procedure presented by Trochkine et al. (2002) and Matsuki et al. (2002), estimated mass flux of dust due to dominating westerly in the free troposphere over the Taklamakan desert from the particle size and number concentrations, and winds observed with the OPC sonde assuming that coarse mode particles are mostly composed of dust particles (Fig. 9.3).

We first estimate volume concentration with equation (1) on the assumption that the shape of coarse mode particles (certainly dust particles) was oval having long axis *a* and short axis *b* (Okada et al. 2001) in order to confirm quantitatively that coarse mode particles were dominant in volume (and mass) concentration of particulate matter. V_j, the volume concentration of aerosol (cm^3/cm^3) in altitude layer *j*,

$$V_j = (4/3)\pi \sum_i a_i b_i^2 n(r_i) j \tag{1}$$

where, r_i is the geometric mean radius of the i^{th} size-bin, $n(r_i)_j$ is the number concentration of particles within in layer *j*, and *j* is the layer number. The values of *a*, *b*, and *r* have the following relations (Okada et al. 2001),

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

and

$$a : b = 1.4 : 1 \tag{3}$$

As shown in Table 9.1, the total volume percentage of large particles (diameter > 1.2 µm) ranged from 88.2% to 94.6% in the height region of 2–10 km, and it is strongly suggested that mass of the particulate matter is largely dependent on coarse mode particle mass and possible to neglect contribution of the fine particles to total mass of particulate matter.

Multiplying the volume concentration at *j*-layer by the density of mineral dust, we can obtain the mass concentration of aerosol particle (g/cm^3) at the *j*-layer, C_j,

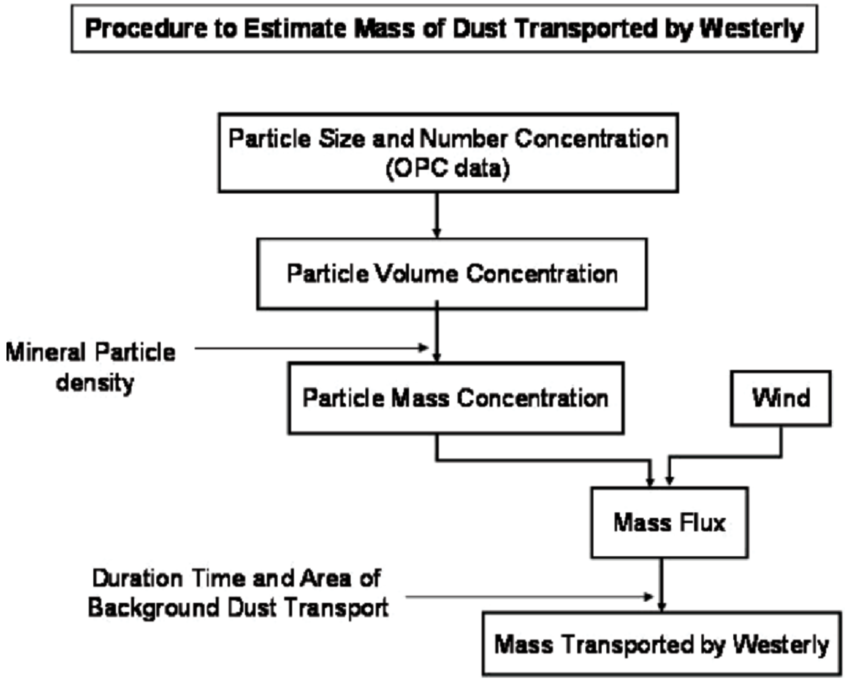

Fig. 9.3 Mass of background Asian dust transported by westerly wind is evaluated on the basis of measurements of aerosol size and number concentrations. Mineral particle density (or external mixing ratio of dust particles) is deduced from analysis of particulate matter collected in the free troposphere

Table 9.1 Volume percentage of large particles

	Date				
Size range	Jan 11, 2002	Aug 27, 2002	Feb 24, 2003	Mar 24, 3003	Oct 24, 2004
Diameter > 0.8 µm	98.5%	93.3%	97.3%	95.5%	96.0%
Diameter > 1.2 µm	94.6%	88.2%	94.5%	86.9%	92.2%

$$M_j = V_j \times \rho, \tag{4}$$

where ρ is the density of mineral and 2.6 g/cm^3 was assumed (Ishizaka and Ono 1982). From the wind speeds and directions at *j*-layer, we can estimate mass flux over the Taklamakan desert area from the following relation,

$$F_j = M_j \times Wind_j, \tag{5}$$

As described before, we focus on mass of dust particles transported long-range by westerly. Equation (3) was modified to equation (4) to obtain the mass flux due to the westerly, F_j westerly,

$$F_j \text{ westerly} = M_j \times [\text{westerly component of Wind}_j] \tag{6}$$

9.4 Results and Discussion

It is suggested, from intensive observations of dust particles from the Taklamakan desert, that the geomorphological feature of the Talim basin and local wind systems on the Taklamakan desert were important factors causing background Asian dust (Iwasaka et al. 2003b, 2004). Therefore it is of interest to discuss mass of the Asian background dust transported by westerly from the Taklamakan desert to downwind.

9.4.1 Mass Concentration Obtained from the Balloon-Borne Measurements in the Free Troposphere

The mass concentrations of mineral dust estimated on the basis of equations (1) and (2) are listed in Table 9.2. High values were frequently observed in the ground atmosphere (1–2 km), and interestingly relatively high concentrations (50 μg/m^3 or larger than it) were frequently detected above about 2 km. Most of the observations showed that mass concentration rapidly decreased above about 5 km, and strongly

Table 9.2 Mass concentration in the height region where westerly wind dominated (μg/m^3)

	Date					
Height	Jan 11, 2002	Aug 27, 2002	Feb 24, 2003	Mar 24, 2003	Oct 24, 2004	Average
4–5	169.8	59.8	10.4	24.2	3.1	53.5
5–6	71.4	60.0	28.7	3.5	3.6	33.4
6–7	1.0	80.9	41.0	4.9	3.8	26.3
7–8	0.8	10.0	71.0	4.8	0.8	17.5
8–9	3.8	*	32.4	4.4	0.8	10.4
9–10	7.4	*	29.3	20.4	0.0	14.3
10–11	0.3	*	3.6	6.3	0.0	2.6
11–12	0.4	*	0.1	0.9	0.0	0.4
12–13	0.1	*	0.1	0.1	0.0	0.1
13–14	0.1	*	0.1	0.1	0.1	0.1
14–15	0.1	*	0.1	0.1	0.1	0.1

* The values were not estimated since measurements of number concentration of the particles with $D > 0.3\,\mu m$ were not good

confirmed suggestion that dust particles were actively removed by westerly winds whose speeds increased above about 5 km (Iwasaka et al. 2003b, 2004).

Iwasaka et al. (1988), from lidar measurements at Japan, estimated total mass loading of weak KOSA centered around the altitude of 300 K potential temperature (1.5–4.5 km) as 1.9–25 μg/m^3 assuming that most of the particles were composed of dust particles and size distribution of particulate matter at those heights was the same with the measurements made near the ground. Therefore this value contained some uncertainties. Trochkine et al. (2002), from aircraft borne measurements over Japan islands, showed dust particle load of 2.3–2.6 μg/m^3 in the altitudes of 3–5 km and suggested importance of long-range transport of dust particles in the free troposphere during calm weather periods.

Taking into consideration that background dust concentrations possibly decrease during long-range transport from the source area to down wind through gravitational deposition and others, the concentration of background KOSA observed over Japan islands is expected to be lower than the values obtained over the Taklamakan desert.

9.4.2 Horizontal Mass Flux Estimated From the Balloon-Borne Measurements

Figure 9.4 shows the vertical profile of horizontal mass fluxes by westerly winds estimated from the values in Fig 9.2 with equations (1), (2) and (3). Most of the profiles suggested active transport of dust in the region where westerly dominated, but fluxes were found to be extremely low on October 24, 2004 compared with other values possibly due to appearance of very stable atmosphere. The lapse rate of temperature is obviously less than the dry adiabatic lapse rate just above the

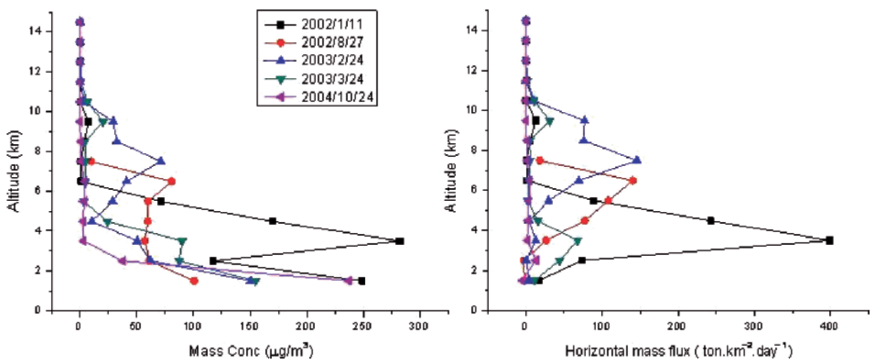

Fig. 9.4 Vertical profile of estimated mass concentration (μg/m^3) and horizontal mass flux (ton/km^2/day) on January 11, 2002; April 30, 2002; August 27, 2002; February 24, 2003; March 24, 2003 and October 24, 2004

Table 9.3 Average, maximum and minimum horizontal mass fluxes of dust (Unit: ton/km^2/day)

	Height (km)										
Flux	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15
Average flux	68.7	46.8	44.0	34.3	22.0	30.4	5.3	0.8	0.3	0.2	0.1
Maximum	242.8	108.1	140.2	145.3	75.8	77.1	10.7	2.1	0.4	0.3	0.1
Minimum	3.0	2.5	1.4	1.2	1.3	0.1	0.1	0.1	0.1	0.1	0.1

ground, and the relative humidity was quite low (<25%). Under the very stable atmospheric conditions, vertical mixing of dust particles becomes very low and supply of dust particles to the regions above about 5 km will be depressed.

The vertical distribution of minimum, average and maximum horizontal mass fluxes of dust are summarized in Table 9.3, showing that the average horizontal mass flux was about in the range of 44.0–68.7 ton/km^2/day in the region of 4–7 km where westerly winds are strong and transport actively dust particles diffusing up from the ground surface of the desert.

It can be strongly suggested, from large horizontal mass flux in the free troposphere shown in Fig. 9.4 and Table 9.3, that mineral dust are effectively transported long-range to downwind by westerly wind in the troposphere, especially on the surface of about 300 K potential temperature, over the Taklamakan desert.

Iwasaka et al. (1988) and Matsuki et al. (2002) stressed the important contribution of background KOSA to biogeochemical cycle of metals and atmospheric constituents in east Asia–west Pacific region since their mass flux in the free troposphere is not negligible comparing with the values of severe KOSA. Matsuki et al. (2002), on the basis of aircraft borne measurements during the days without dust storm episode, estimated the horizontal fluxes due to westerly wind to be in the range of 0.2–7 ton/km^2/day in 2–6 km over Nagoya, Japan. As described before, various deposition and dilution processes are expected during long-range transport of dust, and therefore the difference between the values of both regions possibly suggested those removal and dilution processes.

Zhao et al. (2003), from their model simulations of dust transports in spring of 2001, estimated the horizontal mass fluxes in spring to be in the range of 0.06–2.9 ton/km^2/day over the Sea of Japan and in the range of 0.06–0.35 ton/km^2/day over the North Pacific. It is reported that nearly 20 sandstorm events happened in 2001 spring, at China, and their results can be recognized as examples showing effect of severe KOSA events.

In Table 9.4, the horizontal mass flux estimated here is compared with those obtained over the Sea of Japan, Japan and North Pacific Ocean. In this study, average fluxes during five observations were in the range of 30–68 ton/km^{-2}/day at heights of 4–10 km (Table 9.3). The comparison is made on the basis of very limited measurements and model calculations but possible important contribution of background Asian dust is strongly suggested.

Table 9.4 Horizontal mass fluxes of dust particles: Comparison with other investigations

References	Present study	Zhao et al. 2003	Matsuki et al. 2002	Zhao et al. 2003
Site	Dunhuang, China	Japan Sea (40°N, 130°E)	Nagoya, Japan	North Pacific Ocean (42°N, 140°W)
Condition	Calm weather	Spring	Spring (Calm weather)	Spring
Method	Balloon-borne measurement	NARCM (Northern aerosol regional climate model)	Aircraft observation	NARCM (Northern aerosol regional climate model)
Altitude (km)	4–10	1–10	2–6	1–10
Flux (ton/km^2/day)	30–68 (Average value)	0.06–2.9 (5–250 μg/m^2/s)	0.2–7	0.06–0.35 (5–30 μg/m^2/s)

9.4.3 Importance of Mass of Dust Particles Transported Under Calm Weather Conditions

As described before, horizontal mass flux of dust particles by westerly winds is very large in the free troposphere and it is expected that lots of dust particles are transported by westerly to downwind. The mass transported by westerly winds is given by following relation (Fig. 9.5),

$$\text{Mass} = \text{F (horizontal flux)} \times \text{cross section of the region where westerly is dominant} \times \text{Duration time} \quad (7)$$

where mass flux by westerly winds was already defined by equation (6) and duration time means the time when background dust is transported by westerly winds in calm weather over the Taklamakan desert.

Mass of the dust transported by westerly winds as background dust is roughly estimated to be about 1.4×10^7 ton/year assuming that flux is 5.78×10^2 tons/km^2/day averaging values of 4–5 and 5–6 km in Table 9.3, cross section 800 km^2 considering approximately area of 2 km (height) × 400 km (length in south–north direction), and duration time of 300 days a year.

This value, if westerly wind transports most of the particles which diffuse up to about 5 km from the ground, can be considered as mass of particles which are supplied into the atmosphere and transported long-range as background dust from the Taklamakan desert. The emission of background dust per unit surface area is estimated to be about 4.4×10 ton/km^2/year assuming about 3.2×10^5 km^2 of the surface of Taklamakan desert (emission of background Asian dust). Iwasaka

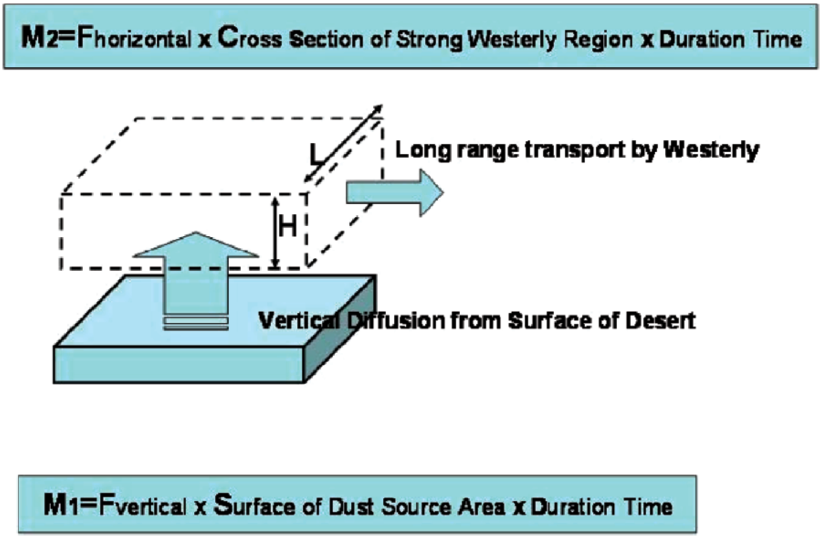

Fig. 9.5 Relation of horizontal mass flux (F horizontal) and mass of background Asian dust flowing out from the Taklamakan desert by westerly wind. Mass of dust particles transported by westerly wind (M2) is approximately equal to mass of dust diffusing into the atmosphere (M1) under the calm weather condition over the Taklamakan desert (see Text)

et al. (1983), on the basis of lidar measurements in Japan, estimated mass load of single severe KOSA, 1.63×10^6 ton, and it is easily suggested that the mass of the flowing out dust is not of negligible levels. Arao and Ishizaka (1986), on the basis of solar radiation measurements at Japan, estimated mass load of Asian dust to be in $4.1–5.3 \times 10^6$ton/year in 30°–40°N region. It is impossible to compare directly the present values and their estimations, but possible to suggest at least important potential of background Asian dust. Xuan et al. (2004) estimated the dust emission of PM10 from the source area in east Asia was 1.04×10^7 ton/year, and their estimation and the present one show reasonable correspondence considering that Xuan et al. (2004) treated all areas as possible dust source regions and only the particles with size larger than 10 µm. Zhao et al. (2003) estimated emission of 21.5 tons/km^2 in spring from source area of Mongolia and China on the basis of numerical modeling. Comparing the present estimations to values given by Zhao et al. (2003), the load of background dust from the Taklamakan desert is a little larger. One possible reason is duration time of background dust from the Taklamakan desert. Background Asian dust can be supplied into the atmosphere in not only spring but also other seasons, and total contribution will become effective. Most of arid and semi-arid regions largely change their surface, especially vegetation, according to seasons, but the Taklamakan desert seems to have potential as source of dust always. Another reason is that we treat only the surface of the Taklamakan desert to estimate emission per unit surface, but their simulation covered very wide area and value of emission was normalized by the surface which included not only strong source areas but also the area having extremely low emission strength. If they treat the mass of emission on only arid area, the value will largely increase. Therefore it is impossible to compare directly the present observations to them, but we can suggest at least that the contribution of background dust from the Taklamakan desert is very large from view point mass balance of dust in east Asia and west Pacific region.

9.5 Summary and Conclusion

On the basis of balloon-borne measurements made at Dunhuang, China during calm weather periods, we discussed mass of background Asian dust transported by westerly from the Taklamakan desert to down wind, and the following results are suggested:

1. The average mass concentrations of background Asian dust were about within the range of 2.6–53.5 $\mu g/m^3$ in the free troposphere over the Taklamakan desert.
2. The average horizontal mass fluxes of background Asian dust were changing within the range of 5.3–68.7 $ton/km^2/day$ in the free troposphere, and mass of dust transported by westerly was about 1.4×10^7 ton/year.
3. It is suggested that the westerly wind largely contributes to long range transport of background Asian dust particles in the free troposphere, and this confirmed previous researches suggesting importance of westerly long-range transport of Asian dust not only in dust storm events but also in calm weather conditions in east Asia to west pacific regions (Duce et al. 1980; Arimoto et al. 1985; Iwasaka et al. 1983, 2004; Uematsu et al. 1983; Gao et al. 1992; Xiao et al. 1997; Uno et al. 2001; Matsuki et al. 2002, 2003; Zhao et al. 2003).

These suggest the possible important contribution of background Asian dust to biogeochemical cycles of not only severe Asian dust but also background Asian dust in east Asia and west Pacific region. The measurements made here, however, are on the basis of only the limited number of balloon-borne measurements which the GPS sensor were mounted on, and much more measurements are desired in the future to obtain better understanding of background Asian dust and its environmental effects. Difference of mass concentration and of mass flux between in dust source regions and in down wind is possibly due to deposition of dust, diffusion in meridian direction and others. It is also necessary to assess the difference and to discuss what processes make the difference in order to understand environmental effects of the fall of background Asian dust.

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