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Dust concentration and flux in ice cores from the Tibetan Plateau over the past few decades

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ABSTRACT

In this paper, we provide the concentrations and fluxes of dust particles (1–30 μm diameter), quantitatively calculated, in several shallow ice cores recovered from the northern (Dunde), western (Muztagata), central (Tanggula) and southern (Dasuopu and Everest) parts of the Tibetan Plateau over the past few decades. Dust concentrations from the northern and western Tibetan Plateau are 2–10 times higher, and from the central Tibetan Plateau is five times higher, respectively, than in the southern part. Dust flux in ice cores is highly dependent on mass concentration, but does not necessarily correlate with accumulation. Dust flux in Dunde (about 798 $\mu g\, cm^{-2}\, a^{-1}$) is 10 times higher, and that in Muztagata (342 $\mu g\, cm^{-2}\, a^{-1}$) is four times higher, respectively, than the dust flux in the central Himalayas (77–103 $\mu g\, cm^{-2}\, a^{-1}$). The quantitative assessment of dust flux in ice cores accords with the aerosol optical depth, and both suggest that the general dust transport route is from northwest to southeast over the Tibetan Plateau. Our results reveal the basic properties of upper level tropospheric dust over the Tibetan Plateau, which is useful for the study of the climatic effects of this dust.

1. Introduction

Atmospheric dust plays an important role in the global climate system. However, because of the great regional distribution and short atmospheric lifetime of dust, its climatic effect is itself an uncertainty (IPCC, 2001). It is hypothesized that atmospheric dust is one of the key factors in Asian monsoon systems. Dust aerosol acts as an 'elevated heat pump' by accelerating and/or enhancing the reversal of the meridional temperature gradient in the upper troposphere between the Tibetan Plateau and regions to the south (Lau et al., 2006), largely by absorbing and scattering solar radiation (Huang et al., 2007). Dust concentration and flux and its spatial distribution are fundamental properties in assessing the dust aerosol's 'elevated heat pump' effect, which may lead to a strengthening of the South Asia monsoon and will influence water cycle and climate for the most populated monsoonal Asia areas. The dust on the Tibetan Plateau comes from the surrounding Asian arid regions and partly from the Plateau itself (Wake et al., 1994; Zhang et al., 1996; Fang et al., 2004). Generally, dust load over the Tibetan Plateau decreases from north to south and from west to east, because of the major Asian dust emission regions located north and west of the Tibetan Plateau and the prevailing Westerlies. However, dust concentrations and fluxes and their regional differences over the Tibetan Plateau are not well understood at present because of the lack of quantitative assessments.

Being adjacent to the Asian arid regions, glaciers on the Tibetan Plateau provide a unique medium for the study of atmospheric dust deposition. The best sources of data for atmospheric dust are thought to be the high resolution ice cores from polar regions and high mountains. Over the past two decades, many studies on dust particles in ice cores or snow samples from the Tibetan Plateau have been reported, such as from Dunde (Thompson et al., 1989), Guliya (Thompson et al., 1997), Dasuopu (Thompson et al., 2000), Puruogangri (Thompson et al., 2006), Chongce (Han et al., 2006) and from other sites (Wake et al., 1994; Xu et al., 2007). Those previous studies provide the basic properties of dust in ice cores and snowpacks over the Tibetan Plateau. Some ice cores contain long-term records over the past thousands of years, while some results were obtained from shallow snowpacks. The short-term records that cover only a few years are insufficient to reveal the long-term average condition of dust in ice cores and are subject to considerable uncertainties because of the large variability in dust

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concentration and flux on annual and seasonal timescales. There are significant differences between the physiographic environments at different sites on the Tibetan Plateau, with semi-arid regions in the north, steppes in the central area, and forest in the southeast. Therefore, an understanding of these considerable regional differences is also required when taking an overall spatial view, since the properties of dust over the Tibetan Plateau are affected by the distance between the Asian dust emission areas and the sampling sites, as well as atmospheric circulation and local conditions.

Another substantial problem when comparing dust particle concentrations in ice cores from the Tibetan Plateau is the size range adopted by different researchers in different studies. For example, for the long Dunde ice core, Thompson et al. (1989) used a size fraction of 2–60 μm diameter; for the Guliya ice core, Thompson et al. (1997) used a fraction of 0.63–50 μm; the fraction >0.63 μm was used for the long Dasuopu ice core by Thompson et al. (2000); Wake et al. (1994) chose the fraction 1–22 μm for the snowpacks in High Asia; the >2 μm fraction was used for a shallow East Rongbuk (Everest) ice core by Xu et al. (2007); and Han et al. (2006) counted particles ranging from 0.66 to 21.4 μm in the Chongce ice core, but preferred the very fine fraction (0.66–1.33 μm) for discussion. Because the number-size distribution of dust particles obeys the Junge law (dust particle number decreases exponentially with increasing diameter), the number concentration will change much more in the fine fraction than in the coarse fraction. And since a few coarse particles of large size have far greater influence on the total volume (mass) than do thousands of ultrafine particles, dust mass concentration will largely depend on the mid-sized and coarse fraction. Therefore, the use of different size ranges will cause significant uncertainty and lower the reliability in the comparison of average grain size, number and mass concentration of dust particles in those ice cores.

Lack of a uniform size range in multiyear records severely impedes the comprehension of the basic properties of atmospheric dust particles in ice cores from the Tibetan Plateau. Well-defined records are required to characterize the temporal and spatial distribution of dust loads on the remote Tibetan Plateau, where field observation is still rare at present. We have discussed the volume-size distribution of dust particles in ice cores (Wu et al., 2009), but not dealt with the concentration and flux. In this study, we quantitatively reconstruct, using a uniform method and size range, the dust concentration and flux in ice cores drilled at typical physiographical locations on the Tibetan Plateau, in order to further the understanding of the mid- and upper-tropospheric dust properties over the Tibetan Plateau, which will be helpful in assessing the radiative effects of the dust.

2. Field work and measuring method

During the past decade, we have drilled some shallow ice cores at different sites in the accumulation zone on the Tibetan Plateau: from Dunde (northern Tibetan Plateau), Muztagata (MA, western Tibetan Plateau), Tanggula (central Tibetan Plateau), Dasuopu (Mt. Xixiabangma) and Everest (southern Tibetan Plateau) (Fig. 1). In order to discuss the vertical variations in dust concentration, we drilled several ice cores (named MA6250 at 6250 m, MA6350 at 6350 m and MA7010 at 7010 m) and collected snow samples at different altitudes at Muztagata. Information on these drilling sites was described in detail in a previous paper (Wu et al., 2009) and is briefly listed in Table 1. We also collected fresh surface snow samples from 6200 to 5400 m, at 50 m vertical intervals, along the mountaineering route at Muztagata on 12 August 2002, when we drilled ice cores there. In order to collect undisturbed snow and to avoid the possibility of post-depositional alteration, surface snow (the uppermost 5 cm) was sampled in the very early morning after a snowfall during the previous night. Samples were collected downwards from the drilling site to the snowline, and all sampling was completed within two hours. Great caution was exercised to avoid possible contamination during sampling and storage.

Table 1. Ice core drilling sites on the Tibetan Plateau.

Site	Location and altitude	Drilling year	Length (m)
Dunde	38°06′N, 96°24′E, 5325 m	2002	17.37
MA6250	38°17′N, 75°00′E, 6250 m	2002	7.89
MA6350	38°17′N, 75°01′E, 6350 m	2001	44.31
MA7010	38°17′N, 75°06′E, 7010 m	2003	33.68
Everest	27°59′N, 86°55′E, 6450 m	2005	22.45
Dasuopu	28°23′N, 85°44′E, 7000 m	2006	17.21
Tanggula	33°08′N, 92°04′E, 5723 m	2005	32.40

We measured concentration and grain size of dust particles using a Beckman Multisizer 3 Coulter Counter (with an aperture of 50 μm and size range between 1 and 30 μm in diameter) in a class 1000 clean room under a class 100 clean hood; we measured oxygen isotopes using a Finnigan Deltaplus and MAT-252, and measured ions using Dionex 2000/2500 ion chromatography. The measurements of dust particles and oxygen isotopes were also described in detail in a previous paper (Wu et al., 2009). Ice core dating was completed by analyzing the periodic variation in profiles of oxygen isotopes, dust and/or ion concentrations, combined with some radioactivity horizons. The degree of dating uncertainty in the timescale is estimated to be about 1 yr above the 1963 horizon. Particle number concentration (C_N), in per millilitres, was calculated from the number in the measurement range; and mass concentrations (C_M), in micrograms per kilogram, were calculated from the volume sums, assuming a mean particle density of 2.6 g cm^{-3}. Since only particles of 1–30 μm diameter were measured, all particles from our ice cores discussed in this paper are restricted to this range, unless specified.

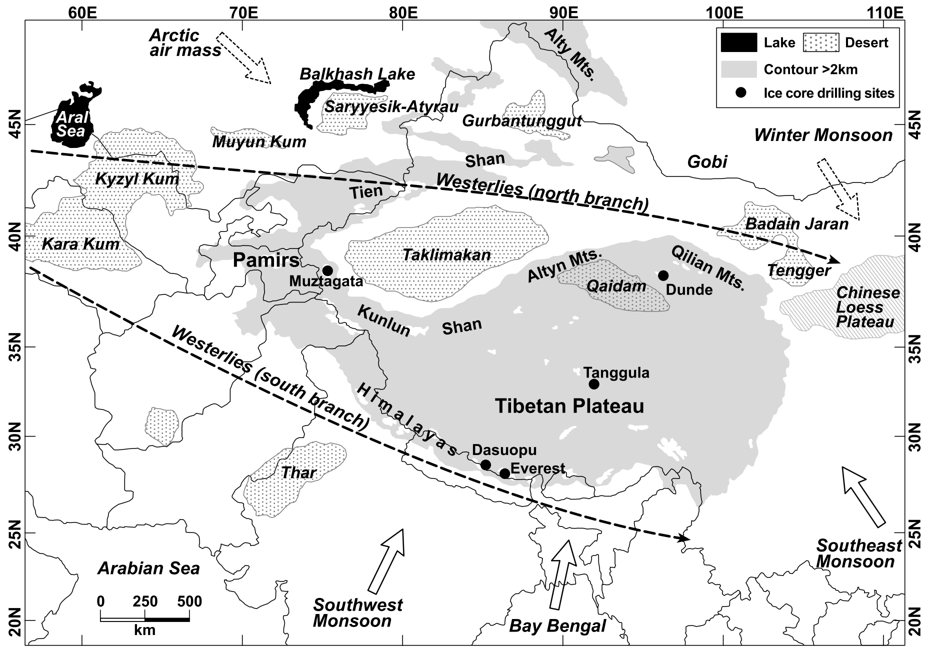

Fig. 1. Location of ice cores drilled on the Tibetan Plateau.

3. Results

3.1. Concentration changes with altitude

Dust concentration in snow/ice cores is subject to the altitudes at which the cores are drilled. Atmospheric dust concentrations for Muztagata fresh surface snow samples are shown in Fig. 2, revealing a clear decreasing trend with increasing altitude. The C_N and C_M at 5400 m are about seven times higher than at 6150 m. The calculated C_N and C_M vertical gradients (which are simply assumed to be linear) between 5400 and 6200 m are about 36 174 particles mL^{-1} per 100 m and 1003 $\mu g\ kg^{-1}$ per 100 m, respectively.

Records from the MA6250, MA6350 and MA7010 ice cores also provide a comparison for the impact of altitude on multi-year average concentrations of dust deposited in alpine glaciers. The C_M averages are 8680, 8921 and 5765 $\mu g\ kg^{-1}$, while the C_N averages are 268 252, 297 362 and 200 451 particles mL^{-1} in the three ice cores located from low to high altitudes, respectively. The average C_N and C_M at 6350 m are 1.5 times higher than at 7010 m, although they cover different periods. Because we only have data from three drilling sites and lack surface samples between 6200 and 7010 m, we cannot give a detailed gradient of dust concentration with altitude at present. However, our quantitative calculation indicates that the decreasing of dust concentration in snow with increasing altitude is significant. Furthermore, the concentration gradient with altitude is expected to vary at different sites because of local conditions.

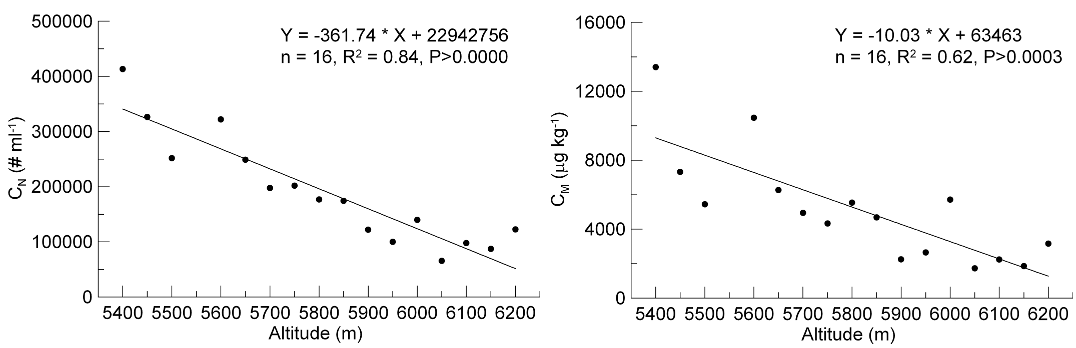

Fig. 2. Dust concentration varies with altitude at Muztagata.

3.2. Regional differences in dust concentration in ice cores

Using different particle size ranges leads to different results in particle number and mass concentrations in ice cores. The fine fraction of dust, such as <2 μm, makes up a large proportion of the total C_N due to the Junge distribution law (particle number decreases exponentially with increasing diameter), while the mid-sized particles contribute most to the total C_M (Wu et al., 2009) and dust flux. In the Dunde ice core, the fine fraction (<2 μm) averages 74% (ranging between 47 and 93%) of the total (1–30 μm) number; however, it only contributes a small percentage (averaging 9.9% and varying from 1.2 to 39%) to the total mass (volume). In the Dasuopu ice core, the <2 μm fraction averages 86% (ranging between 37 and 99%) and 28% (varying from 2.3 to 91%) of the total number and total mass, respectively. In the Dunde ice core, the coarse fraction (>15 μm) averages only 0.04% (ranging between 0 and 0.6%) of the total number; however, it contributes an average percentage of 8.2% (varying from 0 to 45%) to the total mass (volume). This indicates that the fine fraction contributes a relatively smaller amount to C_M but forms a larger proportion of C_N. In contrast, coarse particles provide an extremely small proportion in number but a rather considerable contribution to mass. Therefore, using different particle size ranges can cause large deviations in dust concentration and leads to uncertainties in comparison of dust records from different sites. Our results, using the same particle size ranges, provide much more reliable dust concentrations in ice cores from the Tibetan Plateau.

Dust particle concentrations in each ice core vary over a range of three orders of magnitude, and the ratio of maximum to minimum ranges from hundreds to thousands (Table 2). Although these ice cores cover different time spans, they give a 10-yr average of the particle number and mass concentration and provide the basic characteristics of spatial distribution of dust concentration on the Tibetan Plateau. Average dust concentration also varies significantly at these sites due to the different physiographical environments. In the northern Tibetan Plateau, Dunde has the highest dust concentration among these sites. This is mainly because of Dunde's proximity to the major Asian dust emission areas (e.g. Taklimakan and Qaidam), strong and frequent dust storm events in northern China, and low precipitation. Particle number concentration in Dunde averages 586×10^3 particles mL^{-1}, which is about three, two, three and five times higher than that of the MA7010, MA6350, Tanggula and Everest ice cores, respectively. The average mass concentration displays a similar spatial distribution to the number concentration. Dust mass concentration in Dunde (21 007 μg kg^{-1}) is about 10 times higher than in the Everest ice core and two to three times higher than in the Tanggula and Muztagata cores. The second highest dust concentration site is at Muztagata, western Tibetan Plateau (Pamirs), which is surrounded by the Taklimakan to the east, Kara Kum and Kyzyl Kum to the west, Afghanistan and Pakistan to the southwest. The average dust mass concentrations in Dasuopu and MA6250 m ice cores are comparable to the previous results of snowpacks from Xixiabangma (2300 μg g^{-1}) at 6140 m and from Muztagata (6780 μg g^{-1}) at 5910 m (Wake

Table 2. Dust concentration, flux and accumulation in ice cores from the Tibetan Plateau

		MA6250	MA6350	MA7010	Dasuopu	Everest	Tanggula	Dunde
Covering period		1998–2000	1957–2000	1970–2002	1991–2005	1975–2004	1963–2004	? –2002
Annual layers		3	44	33	15	30	42	
Number concentration	Ave.(arith)	268 252	297 362	200 451	78 294	115 300	187 309	586 399
(# mL^{-1})	SD	338 382	360 719	215 228	91 616	82 616	157 431	1190 966
	Min.	17 560	11 184	9400	7760	12 900	27 000	43 900
	Max.	2529 220	3609 480	2215 880	902 360	664 300	951 060	17 017 200
Mass concentration	Ave.(arith)	8680	8921	5765	1394	1980	10 246	21 007
(μg kg^{-1})	SD	12 963	15 922	6638	2105	2206	11 212	45 366
	Min.	426	308	133	50	170	799	540
	Max.	93 071	269 309	65 681	15 790	20 806	58 764	565 229
Annual net accumulation	Ave.(arith)			610.6	555.3	512.1	230.4	380[a]
(mm w.e.)	SD			310.0	137.2	179.0	60.6	
	Min.			142.7	319.4	170.8	133.7	
	Max.			1390.0	775.8	887.5	367.9	
Annual dust flux	Ave.(arith)			342.4	77.2	103.0	235.4	798[a]
(μg cm^{-2} a^{-1})	SD			224.4	26.6	56.03	170.4	
	Min.			33.8	34.1	20.8	21.8	
	Max.			994.9	119.5	287.0	708.9	

[a]Estimated from multiyear average.

et al., 1994), considering the different sampling altitudes, different size ranges used in dust measurement, and different periods covered. The inner part of the Tibetan Plateau has moderate C_N, which is lower than that in the northern and western Tibetan Plateau, but higher than that in the southern Tibetan Plateau. The C_M in Tanggula ice core (10 246 μg kg^{-1}) is half that of Dunde, but similar to that of MA6250 (8680 μg kg^{-1}) and MA6350 (8921 μg kg^{-1}). The sites in the southern Tibetan Plateau, such as at Dasuopu and Everest, witness the lowest dust concentration: the mass concentration is only about 1/10–1/4 of that in other ice cores, and the number concentration is only about 1/5–1/2 of that in other ice cores. Dust in ice cores from the southern Himalayas (Dasuopu and Everest) is assumed to come from as far as West Asia and, even further, from North Africa, supported by air mass backtrajectory analysis (Carrico et al., 2003). The great distance from dust source areas, large accumulation, and high altitude contribute to the low concentration in this region. The regional difference in dust concentrations over the Tibetan Plateau is in accordance with the previous work (Wake et al., 1994).

3.3. Regional differences in dust flux

Dust concentration in ice cores is controlled by atmospheric dust load, snow accumulation, dry/wet deposition processes, and possible post-depositional alteration (such as wind erosion, redistribution and melting). Here we ignore the dry and wet deposition and post-depositional alteration. Based on the annual layer thickness and the ice density, we reconstructed the annual net accumulation (water equivalent, w.e.) by a simple model, and take it as a substitute for annual precipitation, although the calculated accumulation might not be equal to the actual one.

The Dasuopu ice core has a similar accumulation (averaging 555.3 mm w.e. during the period 1991–2005) to that of the long one drilled at 7200 m in 1997 (Thompson et al., 2000). The latter has an average accumulation of 414 mm w.e. during 1991–1995 and 645 mm w.e. over the past 50 yr (Dr. Keqin Duan, personal communication). Another ice core recovered at East Rongbuk, Everest (drilled at 6500 m in 1997), has an accumulation that averages 581.7 mm w.e. during the period 1954–1963 and 321.2 mm w.e. during 1964–1997 (Qin et al., 2002). The reconstructed accumulation of our Everest ice core (averaging 512.1 mm w.e. between 1975 and 2004) is also rather comparable to the previous result. Therefore the calculated accumulations for Dasuopu and Everest are in accordance with previously reported ones, considering the location effect on the accumulation, large variations in annual accumulation, and the different periods covered. Tanggula ice core has a very low accumulation (averaging 230 mm w.e. during 1963–2004) with snowfall concentrated during summer, making the annual layer very thin.

We calculated the dust's depositional flux by multiplying the accumulation by the annual average mass concentration of each year. Since dust flux shows a large variability, data acquired over many years are necessary. Here we provide the multiyear (15 yr for Dasuopu, 33 yr for MA7010, 30 yr for Everest and 42 yr for Tanggula) average flux in Table 2. Calculation of the dust flux in MA6250 and MA6350 was not undertaken because the period was too short or information on accumulation was not available.

During the field drilling work (October 2002) we found that surface snow on the Dunde ice cap was redistributed by the wind. This post-depositional process may adversely affect the ability to detect periodic variations in the oxygen isotope profiles in the Dunde ice core. Therefore we did not undertake the dating of this ice core in this study. The age of the core is estimated, based on our experience, to be no greater than 40 yr at a depth of 17.37 m. However, taking a long-term view, dust in the ice is still well preserved and the average accumulation rate is scarcely affected on such a huge and flat ice cap, even though it might experience melting during some extremely warm summers. Therefore we can utilize the multiyear average C_M and accumulation to calculate the long-term average dust flux. The average of dust C_M (21 007 μg kg^{-1}) of this study and the long-term annual accumulation (380 mm w.e. from 1850 to 1986) from another long Dunde ice core previously drilled at the same position (Thompson et al., 1989; Davis, 2002) were used to reconstruct dust flux, which is calculated to be about 798 μg cm^{-2} a^{-1} over the past few decades. Being located in the centre of the Northern Chinese deserts, dust flux in Dunde is expected to be the greatest among those sites, combined with the relatively low altitude of the ice drilling site. This result is consistent with our expectation and provides a quantitative assessment. Accurate dating and calculations for a new Dunde ice core are needed in our future work.

Significant spatial differences in dust flux over the Tibetan Plateau were also observed. Dunde has the highest dust flux among these sites, and MA7010 has the second highest (342 μg cm^{-2} a^{-1}), although its altitude is much greater than Dunde and Tanggula. Tanggula has nearly doubled the dust mass concentration (10 246 μg kg^{-1}) of MA 7010 (5765 μg kg^{-1}). However, its dust flux shows a converse trend because MA7010 has an accumulation three times higher than that of Tanggula. In the southern Tibetan Plateau, Dasuopu and Everest display similar dust fluxes at the lowest level of those sites. During the overlapping period (1991–2004), the dust fluxes in Everest (75 μg cm^{-2} a^{-1}) and Dasuopu (76 μg cm^{-2} a^{-1}) ice cores compare well.

4. Discussion

4.1. Asian dust over the Tibetan Plateau

Dust concentration and flux are fundamental parameters in the assessment of the climatic impact of dust. Concentration and flux have different environmental implications. Snow albedo is sensitive to the amount of light-absorbing substances contained in the snow. Dust concentration in snow and ice is a key factor in controlling albedo and subsequent glacier melting under the accelerating global warming perspective, although the causality between dust concentration and glacier melting is not clear. Small amounts of dust particles can increase the absorption of solar radiation in a snowpack by several per cent (Warren, 1982). The ‘elevated heat pump’ effect of dust aerosol (Lau et al., 2006) largely depends upon the dust flux and its spatial and temporal distribution over the Tibetan Plateau. Dust flux in ice cores is a reliable substitute for in situ observation of dust load and is conveniently available for the assessment of dust climatic impact, although some uncertainties exist in our calculations.

The Tibetan Plateau itself is thought to be one of the dust emission areas (Fang et al., 2004), and dust from the Tibetan Plateau was found to possibly contribute to the winter dust storms in East Asia (Han et al., 2008). However, assessment on emission strength of the Tibetan Plateau is in dispute, and some researchers suggest that this strength is weak. Based on ground aerosol sampling, the annual dust deposition rate (local source plus remote source and dry deposition plus wet deposition) on the Tibetan Plateau is estimated to be of the order of about 100 g m^{-2} a^{-1}, which is about only one third of that in the Chinese desert regions (Zhang et al., 2001). This proportion is fairly comparable to the ratio (about one third) of dust flux in the Tanggula ice core to that of Dunde. Further, dust flux in Tanggula is lower than that in MA7010, indicating that the central Tibetan Plateau has a lower dust load than in the western part (the Pamirs). Therefore, the dust emission strength in the central Plateau seems limited.

Local materials contribute to the dust aerosol in the central Tibetan Plateau, accounting for about 70% of the total at Udaoliang (35°12′N, 93°06′E, 4800 m), while material from remote sources occupies the remaining 20–25% (Zhang et al., 1996). Therefore, dust in the Tanggula ice core, which lies close to Udaoliang (250 km north of Tanggula and with a similar natural environment), might also contain some materials from the surrounding environment, although the quantitative contribution of the local and remote (such as Taklimakan) sources is not known at present. Coarse particles (>15 μm) contribute a moderate proportion (17.4%) to the total mass in the Tanggula ice core, higher than that found at the other sites. It is notable that coarse particles in Dunde comprise a relatively small proportion (averaging 8.2% and ranging from 0 to 45%) of the total mass compared with that in Tanggula, suggesting that in the inner Tibetan Plateau the local material provides a greater contribution to dust mass in ice cores than in the northern areas.

The ice core results provide a quantitative assessment of dust flux at different sites and provide clues for dust transport routes over the Tibetan Plateau. From northwest to southeast, dust concentration and flux decrease, with highest values found in Dunde and Muztagata, a high value in Tanggula, and a very low one in Dasuopu and Everest. The Westerlies bifurcate into north and south branches where they meet the Tibetan Plateau at the Pamirs. The south branch mainly goes eastward along the Himalayas and carries dust from West and South Asia, while the north branch goes eastward along Tien Shan, across the Taklimakan Deserts, and along Qilian Shan. Our ice core results are in accordance with the main dust transport route (from northwest to southeast) over the Tibetan Plateau, and consistent with the airborne dust distributions over the Tibetan Plateau and surrounding areas derived from the CALIPSO lidar observations (Liu et al., 2008).

4.2. Dust flux correlation with season, accumulation, and mass concentration

Dust depositional flux changes seasonally because dust storm and precipitation events exhibit strong seasonality. The Dasuopu record displays the clearest annual variations among these ice cores because of the high accumulation and sharp seasonal contrast (Fig. 3). The monsoon (summer) and non-monsoon (winter) seasons of each year were divided (using oxygen isotope and dust profiles) to calculate seasonal accumulation and mass concentration, in order to investigate the dust flux variation on a seasonal timescale. We found that in non-monsoon seasons (with high dust concentration but low accumulation), the average dust

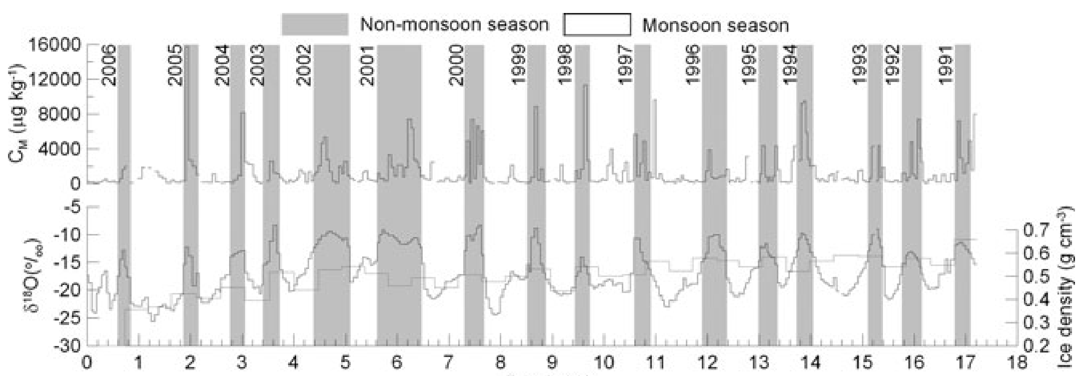

Fig. 3. Seasonal variation of oxygen isotope and dust concentration in Dasuopu ice core.

flux is about 5.6 times higher than during monsoon seasons in the Dasuopu ice core during the period 1991–2005. During monsoon seasons, the average accumulation is about 1.4 times that during non-monsoon seasons, and dust mass concentration is about 1/5 of that during non-monsoon seasons. Therefore, dust flux depends on mass concentration and accumulation to different degrees.

The correlations between flux and accumulation and between flux and mass concentration were investigated (Fig. 4). Dust fluxes in the Muztagata and Everest ice cores display obvious correlations with accumulation, while this relation is only very weakly (in Dasuopu ice core) or not found (in Tanggula ice core) in other sites, suggesting that this correlation varies at different sites and under different conditions. A previous study suggested that at any particular location the variation in atmospheric loading is the main cause of year-to-year variation in dust deposition, while the dust flux appears to be relatively independent of annual snow accumulation (Wake et al., 1994). In contrast to accumulation, dust flux displays a tight correlation with mass concentration at all the four sites, especially at Tanggula. This might be due to the lowest accumulation (230 mm w.e.) found in the Tanggula ice core, which is less than half that of Dasuopu and Everest and even lower (about 60%) than that at Dunde. Even at the same altitude and with similar accumulation, ice cores at MA7010 (7010 m asl and 610.6 mm w.e.) and Dasuopu (7000 m asl and 555.3 mm w.e.) show significant differences in their dust mass concentration and flux: at MA7010 C_N is about 2.5 times higher, C_M is 4 times higher, and dust flux is 4.4 times higher than in the Dasuopu core. This difference suggests that dust input, rather than the accumulation, plays a more important role in dust flux. Our results indicate that dust flux in ice cores from the Tibetan Plateau strongly depends on mass concentration, while the correlation between accumulation and flux varies at different sites, but they are not independent of each other. This result somewhat challenges the previous study on the relationship between flux and accumulation (Wake et al., 1994). Our results also emphasize the importance of using long-term data to get a much more solid result, since the annual variability in dust concentration and accumulation is so large.

4.3. *Comparisons with MODIS AOD index*

The use of satellite data, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD), is a convenient approach to characterize and monitor atmospheric dust load. We calculated the multiyear (from March 2000 to February 2009) average of the MODIS AOD index in order to reflect the atmospheric dust aerosol load over and near the Tibetan Plateau (Fig. 5) and provide a comparison to the result from ice core records. The spatial distribution of AOD shows that the northern and western Tibetan Plateau has a higher aerosol load than in the southern part, also suggesting that the dust transport route over the Tibetan Plateau is generally from the northwest to the southeast. Dust from Taklimakan can be transported southwards into the inner part of the Tibetan Plateau at an altitude of 4–7 km (Huang et al., 2007), as supported by the southeastward decreasing trend of the calculated AOD index, while dust from south Asia, such as the Thar Desert, can be transported eastwards along the southern flank of the Himalayas,

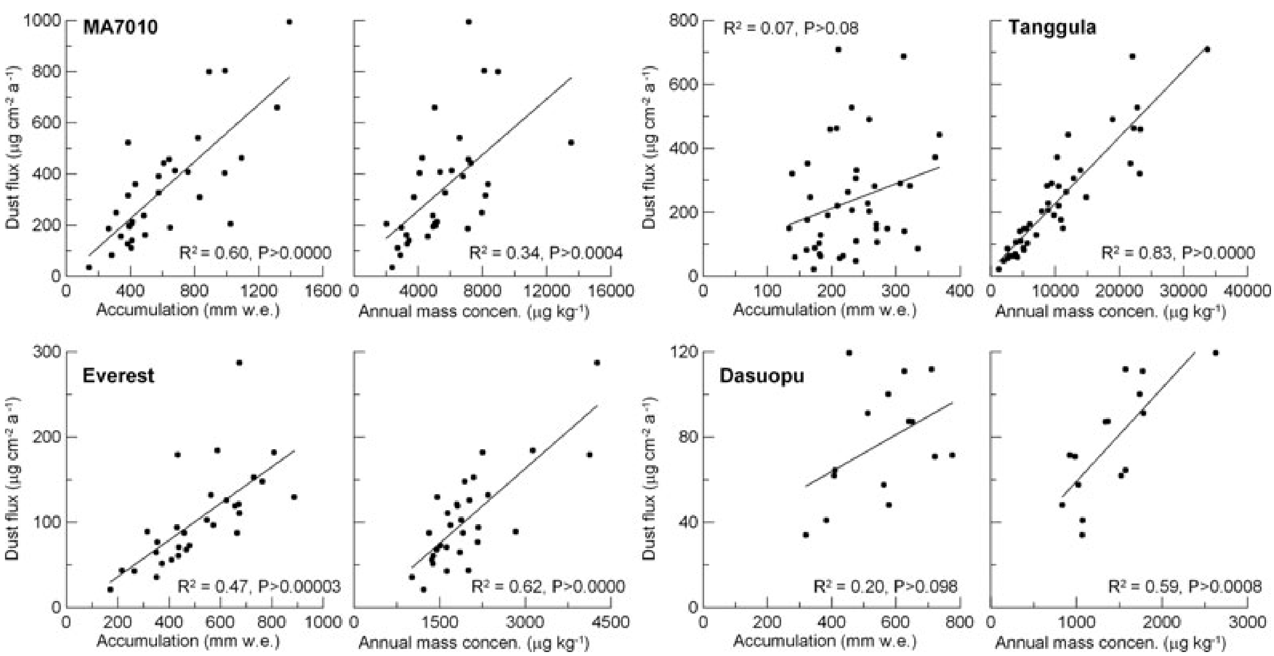

Fig. 4. Plots of dust flux versus accumulation and dust flux versus mass concentration in ice cores.

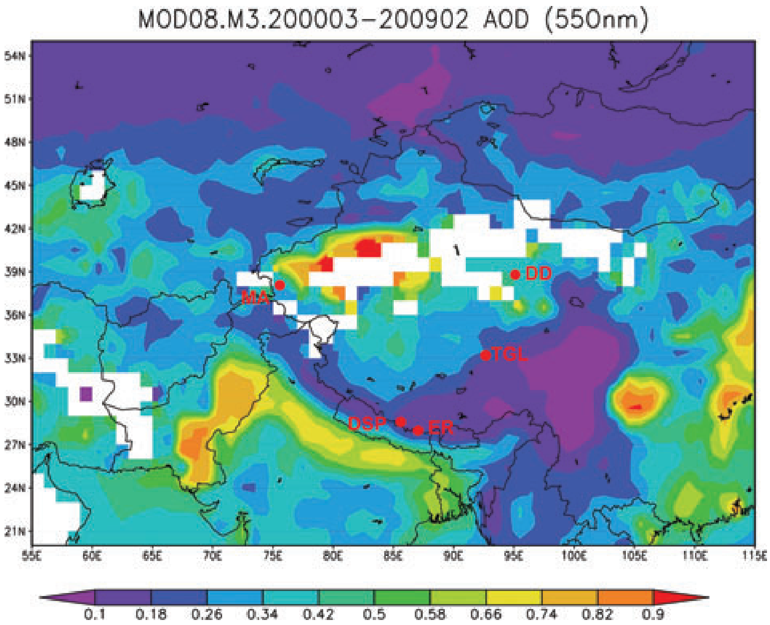

Fig. 5. The calculated multiyear (March 2000–February 2009) average AOD index over and near the Tibetan Plateau. MA: Muztagata, DD: Dunde, TGL: Tanggula, DSP: Dasuopu, ER: Everest.

which acts as a barrier to dust moving northwards into the inner part of the Tibetan Plateau.

Although the dust depositional flux in ice cores is not identical to the actual atmospheric dust load, it provides an approximate analogue for it (Petit et al., 1990). The multiyear average AOD index is the highest (0.34–0.42) over Dunde and Muztagata, moderate (0.18–0.26) over Tanggula, and the lowest (0.10–0.18) over Dasuopu and Everest. The ice core data are consistent with the satellite observation results in the mesoscale characteristics, and provide a quantitative and solid assessment, which can be used to reconstruct the much older dust flux over the Tibetan Plateau by ice core record. Satellite data are very useful in revealing dust aerosol distribution over the remote Tibetan Plateau, especially where field observations and ice core data are rare. However, the MODIS AOD data seem crude and there are obvious discrepancies when compared with the in situ AERONET observation results at Nam Co Station (30°46′N, 90°59′E, 4730 m), where AOD itself is at a very low level over the Tibetan Plateau (Cong et al., 2009). Therefore, based on these discrepancies, caution should be exercised with regard to implications of the MODIS products concerned with the Tibetan Plateau region. Further, the AOD data are available only for the past few years. Therefore, a long-term and reliable representative of atmospheric dust is needed. Dust flux in ice cores may help calibrate the satellite data, since there is a consistency between the two data sets.

4.4. *Uncertainty of the calculated dust concentration and flux*

Some uncertainties also exist in our calculated results. First, we are not clear about the relative proportion of wet and dry deposition processes affecting dust in these ice cores. The aerosol collection at ground sites on the Tibetan Plateau has provided some analogies for this issue, although there is a >1500 m difference in elevation between the ice core drilling location and aerosol sampling site. It has been assessed, based on the dust aerosol collected at Lhasa and Gongga, that wet deposition flux (estimated from scavenging ratios) accounted for less than 10% of the total depositional flux (Zhang et al., 2001). If it is the same case at the ice core drilling site, then dry deposition processes would dominate when the dust falls onto the glacier surface. This seems quite reasonable at Dasuopu and Everest, where high dust concentration and high flux occur during the non-monsoon season with low accumulation (less precipitation). However, at Muztagata, high dust concentration events mainly occur during the precipitation season (Wu et al., 2008) and lead to a much more complex situation for estimating the relative contributions of dry and wet deposition. The field observation of simultaneous precipitation and aerosol chemistry near the Urumqi Glacier No.1 (43°06′N, 86°50′E, 3551 m), Eastern Tien Shan, where dust storm events occur during the precipitation season, indicates that dry deposition contributes approximately one third of the total flux (Zhao et al., 2008). If a similar case occurs at Muztagata, then wet deposition would have a more important contribution than dry deposition. This question remains open because no such field work has been done at these sites.

Second, the dust flux is calculated by multiplying mass concentration by accumulation, and while it is difficult to accurately reconstruct accumulation, it can be obtained by modelling. Since melting is rare at high-altitude sites, such as the MA7010 and Dasuopu ice cores at 7000 m, we can use the calculated value for net accumulation as a substitute for the actual value. What we can provide is the model-based net accumulation, ignoring the possible post-depositional mass loss by melting and redistribution. Therefore, the calculated net accumulation seems lower than the actual one. The dust flux in the Dunde ice core is also a preliminary value since it was simply calculated based on the long-term averaged accumulation and mass concentration. However, at present, there is no better way to reconstruct the actual precipitation from ice cores. We leave elucidation of the calculations as a subject for our future research.

5. Conclusions

Dust particles in ice cores are good representations of Asian dust in the mid- and upper troposphere. The ice cores drilled at Dunde, Muztagata, Tanggula, Everest and Dasuopu provide a 10-yr record of dust properties at different typical physiographic locations on the Tibetan Plateau. Although the number of ice core drilling sites is limited (such as from the southeast of the Tibetan Plateau) and some uncertainties exist, especially in the flux of the Dunde ice core which is rather crudely estimated, our quantitative calculated results are in accordance with the assumption that the dust concentration and flux decrease from northwest to southeast.

Dust concentration and flux over the Tibetan Plateau vary greatly, both spatially and temporally. Dust mass concentration in ice cores from the northern and western Tibetan Plateau is 2–10 times higher than in the south, and that from the central Tibetan Plateau is five times higher than in the south. Dust depositional flux in ice cores is highly dependent on mass concentration, while accumulation displays an uncertain correlation with flux. Although Muztagata has half the mass concentration of that in Tanggula, its accumulation is three times greater than in Tanggula, resulting in a higher flux in the western Tibetan Plateau than in the central part. Dust flux over the Tibetan Plateau decreases from the northwest to the southeast, suggesting a major dust transport route. Being surrounded by dust emission regions, the northern Tibetan Plateau experiences the highest dust flux, which is about 10 times higher than that in the southern Plateau. Dust flux in the western Tibetan Plateau is 1.5 times higher than in the central part, although the former area has a much higher altitude than the latter. The calculated dust flux in ice cores is in accordance with satellite results and, to some extent, may help calibrate the satellite observations. More data from different sites and improvement in the reconstruction of the accumulations are needed to definitively characterize the dust properties over the Tibetan Plateau, in order to get a better assessment on the climatic effects of mid- and upper level tropospheric Asian dust.

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