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Mineral dust layers in snow at Mount Tateyama, Central Japan: formation processes and characteristics

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ABSTRACT

Deposition of water-insoluble dust was measured in winter snow deposited at Murododaira (2450 m) on the western flank of Mount Tateyama in central Japan. An analysis of temporal variation in atmospheric aerosol concentration, incremental snow height and concentration of dust in the snow cover suggests that wet deposition is the major process in forming thicker dust layers in the snow cover at Mount Tateyama. Dust layers in the snow cover contain Ca-rich materials typically found in Asian dust (Kosa) particles. Volume size distributions of dust particles in the snow showed single and bi-modal structures having volume median diameters from 6–21 μm. Dust profiles in snow cover over the last 6 yr reveal frequent sporadic high dust concentrations in spring and large year-to-year variations in the amount deposited. The average amount of dust deposition (7.7 g m^{-2}) from winter to spring at the site was close to the long-term averages of annual flux obtained from sea sediment near Japan, implying that dusty precipitation in spring contributes to annual deposition of aeolian mineral dust.

1. Introduction

Windblown mineral aerosol particles derived from the crustal surface are an important atmospheric component. Aeolian dust particles are inferred to be an important component in accumulation of pelagic deep-sea sediment (see reviews in Windom, 1969; Prospero, 1981; Duce, 1995), while they contribute to nutrient input to the ocean surface (Duce, 1986; Talbot et al., 1986; Zhang and Liu, 1994) and affect the Earth's radiation budget (Nakajima et al., 1989; Andreae, 1995; Tegen and Lacis, 1996). Atmospheric transport processes (Iwasaka et al., 1988; Merrill et al., 1989; Uno et al., 2001) and transformation processes of the dust particles (Nishikawa et al., 1991; Dentener et al., 1996) were also studied to characterize the geochemical role of aeolian dust events in the Asia–Pacific region. These dust events (reducing horizontal visibility to below 10 km at ground level) have been observed frequently in spring over Japan (Koizumi, 1932; Arao et al., 2003), the so-called Kosa phenomenon.

Ground-based measurements of aeolian dust deposition have inherent problems engendered by contamination of surrounding soil (Uematsu et al., 1985). Although grain size analysis of the dust collected on the ground would provide an insight into the fraction contributed by locally derived sand, it is difficult to estimate local silt and clay fractions (Inoue and Naruse, 1987). An analysis of pelagic deep-sea sediments provides 100- to 1000-yr scale averages for windblown mineral dust deposition with some long-term geographical variations (Rea and Leinen, 1988; Masuzawa et al., 1989). However, the source of deep-sea sediments may include horizontal transport of minerals from continental shelves. Furthermore, its analysis does not provide insight into the short-term variability of dust deposition or atmospheric deposition processes because of the very low accumulation rate of the deep-sea sediments. Information on wet and dry deposition processes is needed to properly model atmospheric transport and the deposition of dust particles (Mahowald et al., 1999). Explorations of wet deposition processes of dust particles are rather limited, but several studies have addressed dry deposition processes (e.g. Ruijrok et al., 1995; Arimoto et al., 1997). Moreover, they have been conducted mainly at ground level because of the difficulty of making measurements within clouds. Davidson et al. (1996) reviewed these deposition processes at high-elevation sites such as the summit of Greenland. As they pointed out, however, numerous uncertainties plague estimates of deposition processes.

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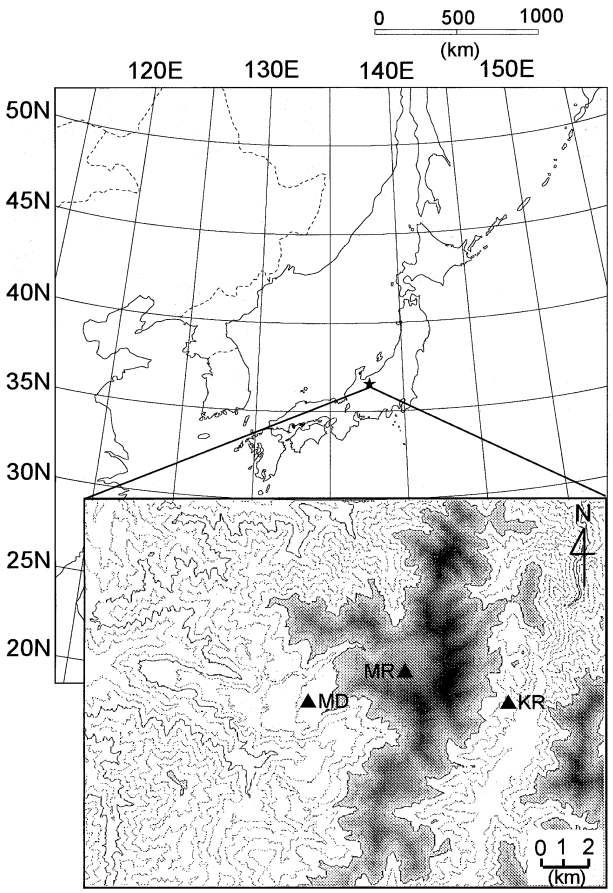

Fig 1. Map of Mount Tateyama in Japan with three sampling sites: Midagahara (1830 m, abbreviated as MD), Murododaira (2450 m, MR) and Kurobedaira (1780 m, KR). Contour lines in the map represent intervals of 200 m. Shaded areas indicate an altitude above 2000 m; the darker tone represents higher altitudes.

The northwest side of the Japanese Alps on Honshu Island, which faces the Sea of Japan, has heavy snowfall during the winter because of strong northwesterly winds (winter monsoon). Mount Tateyama (3015 m above sea level (asl)) is located in the Hida range of the northern Japanese Alps (Fig. 1). Snow cover at Mount Tateyama in spring is about 6–10 m; it remains from November to July. Air temperature rarely exceeds freezing from November to April (Nakagawa et al., 1976). Mountain snow cover during the subzero period provides useful information on deposition of aeolian dust transported far from the Asian continent because snow cover prevents windblown redistribution of local soil materials on the ground. Chemical analysis and meteorological correlation suggest that the dusty dirt layers found in the snow cover at Tateyama are formed by deposition of atmospheric Kosa dust particles (Osada et al., 2000). However, the processes of formation of the dust layer and characteristics of the dust particles in the snow cover remain unclear. Furthermore, the amount of dust particles deposited close to the snow-forming cloud altitude may provide a useful insight into the free-tropospheric fraction of dust deposition over the northwest Pacific region.

This study analyses the relationship between temporal variation in atmospheric aerosol concentration and vertical distribution of water-insoluble dust concentration in the snow cover at Murododaira (36°34′ N, 137°36′ E, 2450 m asl, hereafter MR), on the western flank of Mount Tateyama, to elucidate the process of formation of the dust layer in the snow cover there. Second, we show lateral continuity of dust layers in the snow cover around Mount Tateyama. Then, we characterize the dust found in the snow in terms of its correlation with chemical data and volume size distribution. Finally, we summarize the amount of dust deposited at MR from winter to spring and compare it with other flux data near Japan.

2. Snow samples, laboratory analysis and aerosol measurements

Figure 1 shows a location map of Mount Tateyama with three sampling sites: Midagahara (1830 m, abbreviated to MD hereafter), Murododaira (2450 m, MR) and Kurobedaira (1780 m, KR). The main station of our study is MR. Hand-dug pit works have been undertaken every spring since 1994. In winter, several snow pits were also dug at MR to obtain auxiliary data sets for density, water-insoluble dust, chemistry and stratigraphy. This is important for determining the parameters of a snow densification model and for studying the development of stratigraphic markers. The sampling sites MD and KR were used to show regional continuity of the dust layers in the snow cover. Vertical snow samples were obtained from hand-dug 3–8 m deep pits at the sites. The snow deposition environment at MR is suitable for continuous snow accumulation because there is a flat tableland of about 200 × 200 m and an open view to the west side toward the Sea of Japan. Similarly, the topographies of the MD and KR sites are nearly flat; therefore they are suitable for uniform snow deposition.

A battery-powered ultrasonic snow height detector was installed at MR to measure snow increments every 30 min. Snow height data were stored in a data logger with other meteorological parameters. However, severe meteorological conditions (strong winds and heavy rime ice) hindered measurement of snow height; the instrument was often unable to measure during the winter.

We worked on the snow pits before the snow melted because chemical and dust constituents may redistribute due to water percolation. After recording snow stratigraphy, clean, fresh vertical sections were exposed for dust and chemical snow sampling. We collected snow samples, typically 100 g, in 10 cm increments using a pre-cleaned stainless steel shovel and polyethylene gloves. Samples were stored in Whirl-Pak bags (NASCO) and kept frozen until further analysis. Snow density, snow temperature and snow grain size were measured for the same horizontal layers. Samples were quickly melted in a microwave oven and immediately filtered through pre-weighed 25 mm diameter,

0.2 μm pore size Nuclepore filters (Coaster Corp.) in our laboratory to avoid wall adhesion of particles after melting. After drying the filter at 45 °C for more than 3 h in an electric oven, we weighed the filters on an electric microbalance (ER182A; A&D, measurable to 0.01 mg). The water-insoluble dust weight typically includes organic and biogenic components. However, during the winter more than 90% of the weight consists of mineral dust (Miyamoto, 1999). In this study, we used the weight of water-insoluble dust as the mineral dust. Procedural blank values for filter and snow sample handling including particles from the wall of the sampling bag were obtained using 100–200 g of ultrapure particle-free water (Milli-Q; Millipore). Blank values were within the replicative error of the microbalance (±0.02 mg). Ionic concentrations in the filtered meltwater samples were analysed by ion chromatography. Details of chemical analyses are described in Osada et al. (1998, 2002). The volume size distribution of water-insoluble dust particles in the remaining meltwater samples was measured by a laser diffraction/scattering particle size distribution analyser (LA-300; Horiba Instruments, Inc.) with a measurable size range of 0.1–600 μm. Particle size distribution was determined using a volume-scattering function and diffraction patterns of a laser beam at 650 nm. Note that this instrument provides only volume size distribution data, and does not act as a laser particle counter for the absolute volume of size-segregated dust particles. Meltwater samples with dust particles were agitated before measurement. For our meltwater samples from high-elevation sites, aggregation and coagulation of dust particles in the sample water were negligible for several days after melting, probably as a result of the lower contribution of adhesive organic materials (e.g. plant wax, etc.) in winter snow (Miyamoto, 1999). Replicate (five times) measurements showed a low percentage of variability for median diameters.

We measured the number size distribution of atmospheric aerosol particles with a laser particle counter (KC-01C; Rion Co. Ltd) installed on 27 January 1999 at the Hotel Tateyama in Murododaira. The laser particle counter measures the number of aerosol particles for five size ranges: larger than 0.3, 0.5, 1.0, 2.0 and 5.0 μm in diameter. During the winter monsoon period, strong northwesterly winds prevailed with frequent snowfall. We installed a snow-clogging preventer similar to the "Frisbee sampler" in Heidam et al. (1993) at the tip of the inlet tube above 2 m. Sampling losses caused by the inlet tube were estimated as 38% for 5 μm, but number–size data were not corrected in this study. Details of the atmospheric measurements are found elsewhere (Osada et al., 2003).

3. Results and discussion

3.1. *Process of formation of the dust layer in snow cover at Mount Tateyama*

Figure 2 shows the relationship between time variation (column (a) snow height and aerosol volume concentrations larger than 0.3 μm) and the vertical profile of dust concentration of snow

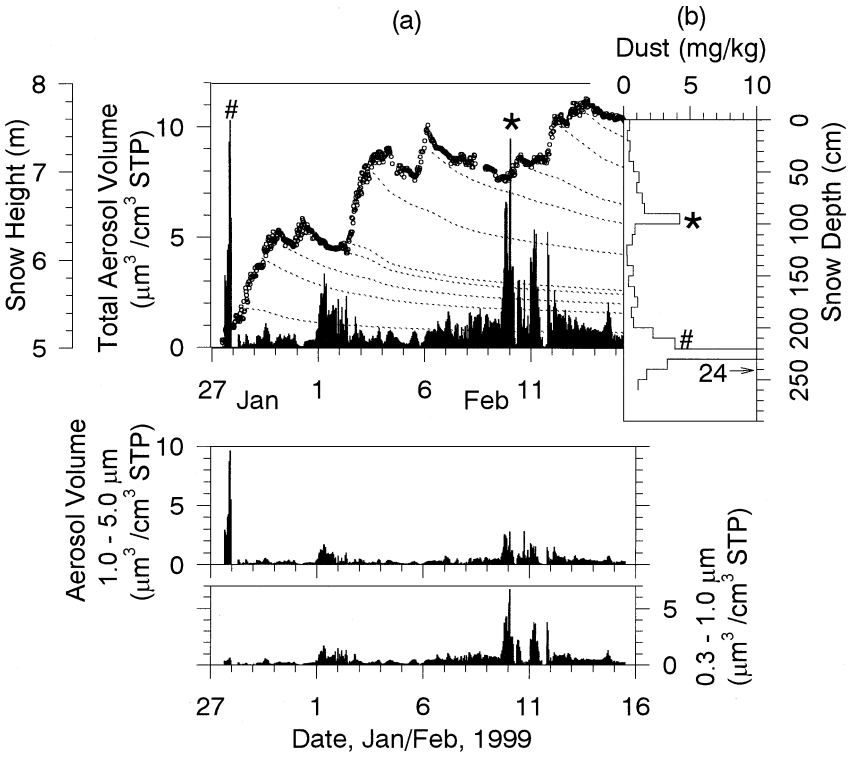

Fig 2. (a): Temporal variation in snow height (circles) and total (>0.3 μm) volume concentration of aerosols from 27 January to 15 February 1999. Dotted lines in (a) represent daily isochrone height. (b) Vertical profile of dust concentration on 15 February 1999. The lower panels of (a) are volume concentrations of supermicron (1.0–5.0 μm) and submicron (0.3–1.0 μm) aerosols.

(column (b)) corresponding to 27 January–15 February 1999. Figure 2a shows the daily isochrone height estimated from a snow densification model of dry snow (Motoyama and Kojima, 1985) as slanting dotted lines. The daily isochrone height represents a hypothetical plane of snow surface buried in a day. During snowfall, the daily isochrone height decreases with increasing snow weight because snow layers below the plane compact concomitantly with the load and physical properties of snow. In the densification model we used 130 kg m^{-3} as the initial snow density at the surface observed on 15 February 1999. The value for a compactive viscosity coefficient of mountain snow during winter was obtained from Nakagawa et al. (1976). The vertical scale of the dust profile in Fig. 2b was adjusted to fit the difference in the snow height during 15 February–27 January, corresponding to the snow surface and the horizon just above a high dust peak (marked by # in Fig. 2b) found in the snow on 27 January. On 27 January, we sampled snow at MR and installed the atmospheric instruments. Snow that had fallen during the night was light yellow; its dust concentration was 12.7 mg kg^{-1}. According to meteorological and snow observation at the site, the dust flux at this time was estimated as 0.5 g m^{-2} day^{-1}. From 26 to 27 January 1999, Kosa phenomena were widely reported in western Japan (Japan Meteorological Agency) and in Korea (Kim and Park, 2001; Chun et al., 2001). Sporadic "red snow" events causing high dust flux were observed occasionally (e.g. 15 g m^{-2} for a 2-day event at Shishiku, near Kanazawa: Tsunogai et al., 1972). The amount of atmospheric input of mineral dust to the western North Pacific region has been estimated as 0.8 g m^{-2} yr^{-1} for the open ocean to 21 g m^{-2} yr^{-1} for the coastal area (Uematsu et al., 2003). Although the event is sporadic, dust deposition associated with "red or yellow snow" may contribute greatly to annual flux.

Size-segregated (0.3–1.0 and 1.0–5.0 μm) volume concentrations of aerosols are also presented in the lower panels of column (a) in Fig. 2. The volume concentration of aerosols is normally lower during snowfall such as from 28 to 29 January, 2, 3 and 5 February, etc. and higher during times of no precipitation such as 31 January to 1 February, and 6–9 and 14 February. Higher aerosol volume concentrations, especially of supermicron aerosols, during snowfall were found as indicated by # (27 January) and * (10 February). According to the daily isochrones, the snow layer formed on 10 and 11 February corresponds to a depth range 90–100 cm below the surface on 15 February. Although the volume concentration of supermicron aerosols was 2.8 μm^3 cm^{-3}, the dust concentration (4 mg kg^{-1}) in the snow layer was clearly discernible as a peak. This suggests that a coincidence of high aerosol volume concentration and snowfall is essential in forming a peak of dust concentration in snow. We cannot rule out the contribution of dry deposition of dust particles. For example, a small hump at 180 cm depth in Fig. 2b could result from dry deposition on 1 February because the volume concentration of supermicron aerosols on that day was relatively high (1.7 μm^3 cm^{-3}). However, dust concentration in snow at a depth of 180 cm was about 1 mg kg^{-1} at most, which is much lower than the peak (4 mg kg^{-1}) at a depth of 90 cm on 10 February. Dry deposition during 6–9 February may also contribute to the peak at 90 cm, but it should be smaller than 1 mg kg^{-1} because of a low concentration ($< 1 \mu m^3$ cm^{-3}) of supermicron aerosols during this period. On the other hand, the dry deposition process should form very thin layers instead of several cm to >10 cm thick dirt layers in the snow. Visibly coloured dirt layers in the snow on 15 February were found for 80–95 cm (corresponding to * in Fig. 2b) and 210–240 cm (# in Fig. 2b) depths. Thus, a combination of high aerosol volume concentrations in the supermicron mode during snowfall may only form a thicker dusty layer. A high dust deposition flux dominated by the wet process has also been reported for the North Pacific region when both rainfall and high atmospheric dust concentrations coincide (Uematsu et al., 1985; Duce, 1995).

3.2. *Horizontal distribution of dust layers and snow height*

If the depositional environment of snowfall is continuously ideal without redistribution of snow, atmospheric signals such as mineral dust deposition should be preserved in sequence in the snow layers (Langway, 1970; Fisher et al., 1985). To confirm regional uniformity and suitability of snow analysis at Mount Tateyama as archives of the atmospheric dust deposition during winter, snow samples were obtained from two additional sites: MD (Midagarhara, 1830 m, 4.5 km west of the main site) and KR (Kurobedaira, 1780 m, 5 km east of the main site).

Figure 3 shows three vertical profiles of dust concentration in spring 2001. Water-soluble constituents in the snow cover may have been redistributed from their original layer because snow temperatures of the upper part of the snow cover at MD and the entire depth of KR were zero at the time of snow sampling. Poor correlation for the upper part of the dust profiles probably results from surface melt at lower elevation sites and different sampling dates. However, most water-insoluble dust profiles resemble each other, as indicated by the dotted lines representing significant dust peaks. Strong lateral correlation of the dust peaks suggests regional uniformity of dust deposition events and the suitability of snow analysis at Mount Tateyama as archives of the atmospheric environment.

Numbers at the bottom of each column in Fig. 3 are amounts of dust deposited per unit area during the winter. These values are almost identical, ranging from 10.4–13.9 g m^{-2}. Snow sampling dates ranged from 27 March to 20 April (24 days), which includes the main period of frequent Kosa phenomena. According to aerosol measurement data during this period (Osada et al., 2003), the number of days exceeding a volume concentration of 10 μm^3 cm^{-3} for supermicron aerosols was 11 days, that is, 46% of the period. However, the amount of deposited dust from the winter to the sampling date did not differ greatly among the profiles. This implies that the contribution of dry deposition onto the snow surface is not large in dust deposition flux, even in spring.

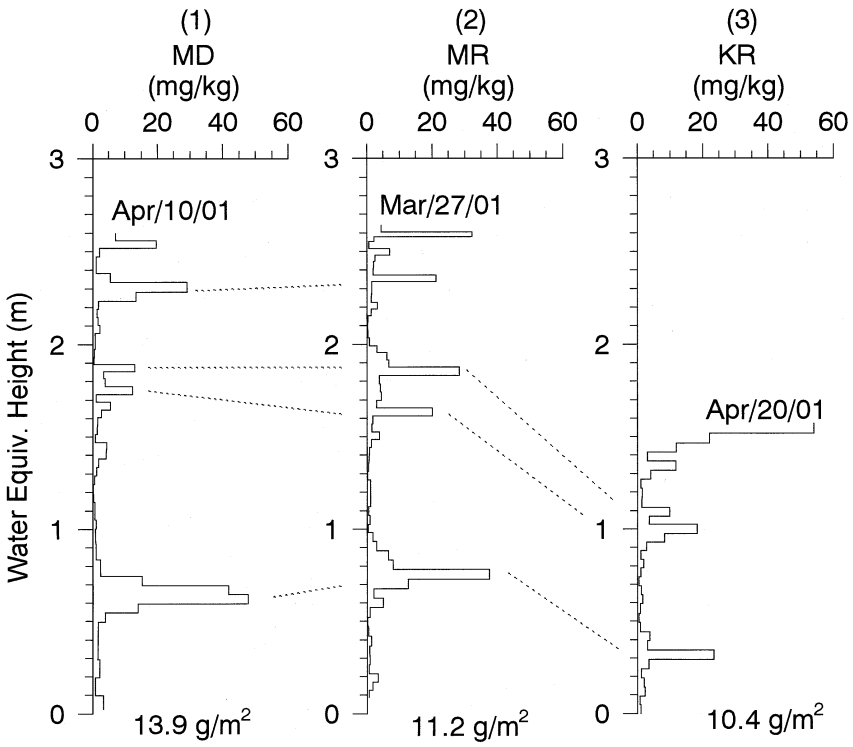

Fig 3. Vertical profiles of dust concentration in spring 2001. Columns (1) to (3) indicate results from Midagahara (MD), 1830 m; Murododaira (MR), 2450 m; and Kurobedaira (KR), 1780 m. Dates shown above the dust profiles are sampling dates. Values at the bottom represent the amount of dust deposition from winter to spring.

Figure 4 shows monthly and daily precipitation at Kamiichi (296 m asl, 25 km northwest of Mount Tateyama, data from the monthly meteorological report of the JMA) and daily average of aerosol volume concentration larger than 1 μm from November 2000 to December 2001 (Osada et al., 2003). Amounts of monthly precipitation were high in January, June and September, respectively corresponding to winter monsoon, Baiu and Shurin, with typhoon periods common in western central Japan (Arakawa and Taga, 1969; Maejima, 1980). Note that the cumulative amount of precipitation from November 2000 to March 2001 at Kamiichi is about 1.4 m of water equivalent height, which is about half of the water-equivalent snow height at MD and MR, and almost equal to KR. Higher snow accumulation in the western parts (MD and MR) of the mountain summit results from orographic increase of snow fall at the high-elevation sites under the westerly winter monsoon conditions. However, the orographic effect varies by less than 100%, as seen in difference between Kamiichi and MR.

Precipitation is frequent during the winter monsoon, but aerosol concentration is low. Although the amount of precipitation is large in January, the amount of dust deposition is typically negligible except for "red snow" events as discussed before. As reported elsewhere (Osada et al., 2003), a "red snow" event was also observed at a town near Mount Tateyama and at the Takada Meteorological Observatory on 3 January 2001. The dust peak at 70 cm height for MR in Fig. 3 may correspond to this.

In spring, the activity of the winter monsoon is weakened; then, Kosa is frequently observed under clear skies associated with a moving anticyclonic system from the Asian continent towards Japan. Consequently, the frequency and amount of precipitation decrease in this season as of April in Fig. 4. Instead, the chance of a combination between a cold front (precipitation) and Kosa particles at the fringe of a moving anticyclone may increase in spring, such as in March, which provides an effective opportunity for the wet deposition of free tropospheric supermicron aerosol particles.

3.3. Characteristics of dust in snow: ionic constituents and volume size distribution

Figure 5 shows an example of the relationship among ionic concentrations, pH and dust concentration obtained at MR in March 2001. Most Na^+ in the snow at Mount Tateyama originates from sea salt, based on significant correlation with Cl^- and Mg^{2+} concentrations (Osada et al., 2000). Vertical profiles of dust concentrations are similar to variations in Ca^{2+} concentration and pH, but not Na^+ concentration. The contribution of sea salt Ca^{2+} to the total Ca^{2+} content was small (13% on average). Dust peaks found in mountain snow are inferred to originate from arid regions in the Asian continent because high alkaline Ca is a tracer of mineral dusts from desert and loess areas in the Asian continent (Ichikuni, 1978; Suzuki and Tsunogai, 1988).

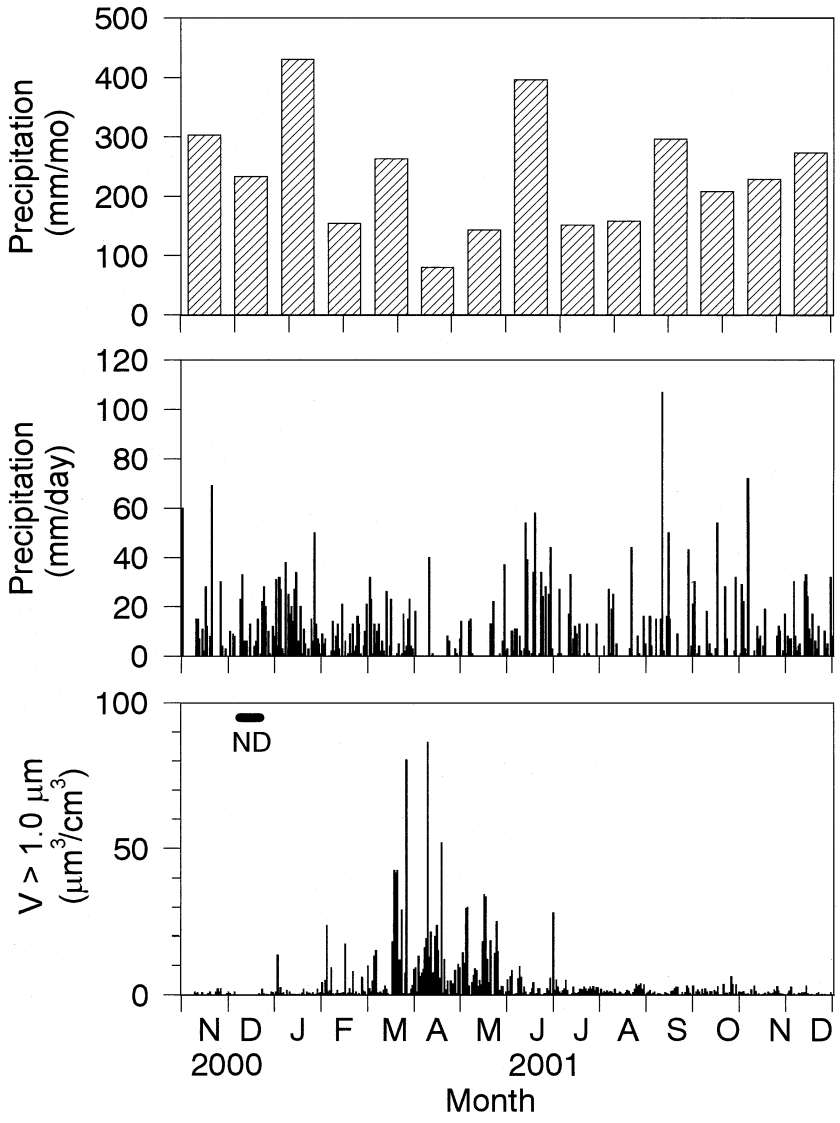

Fig 4. Seasonal variation of precipitation at Kamiichi and aerosol volume (>1.0 μm) at Mount Tateyama from November 2000 to December 2001. ND: no data.

Table 1. Parameters of volume size distributions

Sample	Dust conc. (mg kg^{-1})	D_1 (μm)	σ_1 (μm)	D_2 (μm)	σ_2 (μm)
(a)	32.3	10.1	1.8	17.8	1.5
(b)	6.9	6.0	1.8	21.3	1.7
(c)	21.2	6.6	1.9		
(d)	28.3	21.0	1.9		
(e)	20.1	8.8	1.6	15.0	1.5
(f)	37.5	5.8	1.7		

D_1 and D_2 represent mean diameters of lognormal distributions.
σ_1 and σ_2 indicate the standard deviation of the distributions.

Figure 6 shows volume size distribution of the dust particles in the snow layer (a–f) in Fig. 5. These dust layers are distinguishable as dirt layers by inspection at the site. Table 1 lists size parameters fitted with lognormal distributions (Jaenicke, 1993; Hinds, 1999). The volume median diameters of the dust particles range from 6 –21 μm. Some dust layers comprise two modes such as (a), (b) and (e). In the Spanish Mediterranean area, the mean size fraction of dust particles in "red dust rain" ranges from 4–30 μm with a bimodal structure of about 4–7 μm and 18–22 μm (Sala et al., 1996). Mean dust diameters of 4–16 μm have also been reported for Crete (Nihlén et al., 1995). Dust analysis of the snow at Monte Rosa in the Swiss Alps (Wagenbach and Geis, 1989) showed mean volume diameters of background and Saharan dust of 2.5 and 4.5 μm respectively. They also reported variation in mean volume diameter from 2.5 to 10 μm for visible Saharan dust layers. The volume size distribution of dust in glaciers in central Asia exhibits similar size ranges (Wake and Mayewski, 1994). Median diameters of dust in snow and ice cores from Greenland,

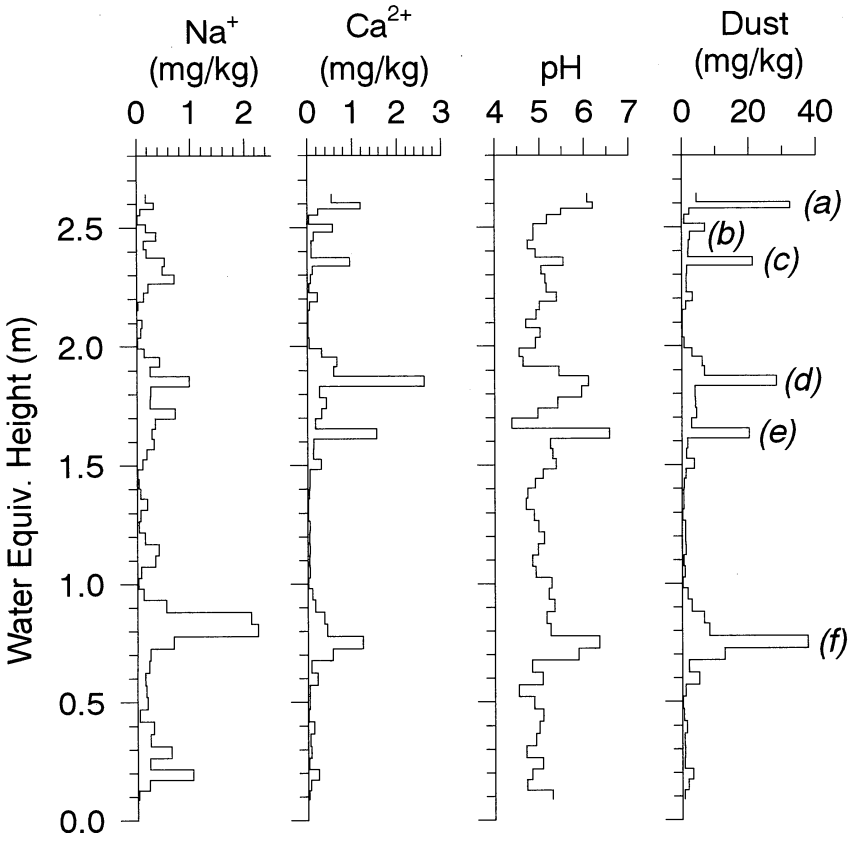

Fig 5. Vertical profiles of ionic concentrations (mg kg^{-1}), pH and dust concentration (mg kg^{-1}) at MR on 27 March 2001. Letters (a)–(f) in the dust profile indicate visibly distinguishable dust layers.

Penny Ice Cap, and Antarctica were about 1–2 μm (Steffensen, 1997; Zdanowicz et al., 1998; Delmonte et al., 2002; Ruth et al., 2003).

Our results show much larger median diameters compared with polar snows, but they are similar to visible dust layers in the snow at Monte Rosa and the "red dust rain" in the Spanish Mediterranean. The larger volume median diameter appears at sites closest to source regions. According to data for backward air trajectories from Mount Tateyama (Osada et al., 2003), the typical transit time from possible major source regions (Gobi desert in Mongolia and Badain Jaran Desert in northern China, Sun et al., 2001) to Mount Tateyama (about 3000 km distant) was 1.5–2 days for winter to early spring. A recent study (Maring et al., 2003) of the change in size distribution during trans-Atlantic dust transport suggested that a major shift of size distribution may occur within 1–2 days of transport. The volume median diameter is larger than that found in polar areas and is highly variable, probably because of changes during initial transport because Mount Tateyama is located at about this time range of transport from the source region. Furthermore, occasionally observed bi-modal distributions imply mixing of dust particles from different source locations or wind conditions. Although our preliminary analysis of backward air trajectory showed no conclusive differences for source regions between mono- and bi-modal dust events, further systematic representative measurements of very large aerosols and modelling studies may provide insight into variations in size distribution.

3.4. Amount of dust deposition at Murododaira

Figure 7 shows vertical profiles of dust concentration in snow samples at MR for the last 6 yr. Dust concentrations are generally lower in the bottom part and higher in the upper part of the snow cover. Snow layers in the bottom part are deposited from November to January when Kosa phenomena are rarely reported. From January to February, the winter monsoon brings heavy snowfall with very low dust concentration in this area. For the past 6 yr, two profiles obtained for 1999 and 2001 show dust layers in the middle to lower part of snow cover deposited in January, as mentioned previously. Dust peaks in other profiles are found mainly in the upper part. The likelihood of a combination of snowfall and a higher atmospheric dust concentration also increases in spring because free tropospheric concentrations of supermicron aerosols (Osada et al., 2003) and Al concentrations on the ground (Tsunogai et al., 1988) are higher in spring than in winter.

Table 2 lists amounts of dust deposition measured for the snow cover at MR from winter to spring. Values were estimated from dust concentration, snow density and vertical increments of the sample. Note that the dust deposition (2.9–11.2 g m^{-2}, 7.7 g m^{-2}

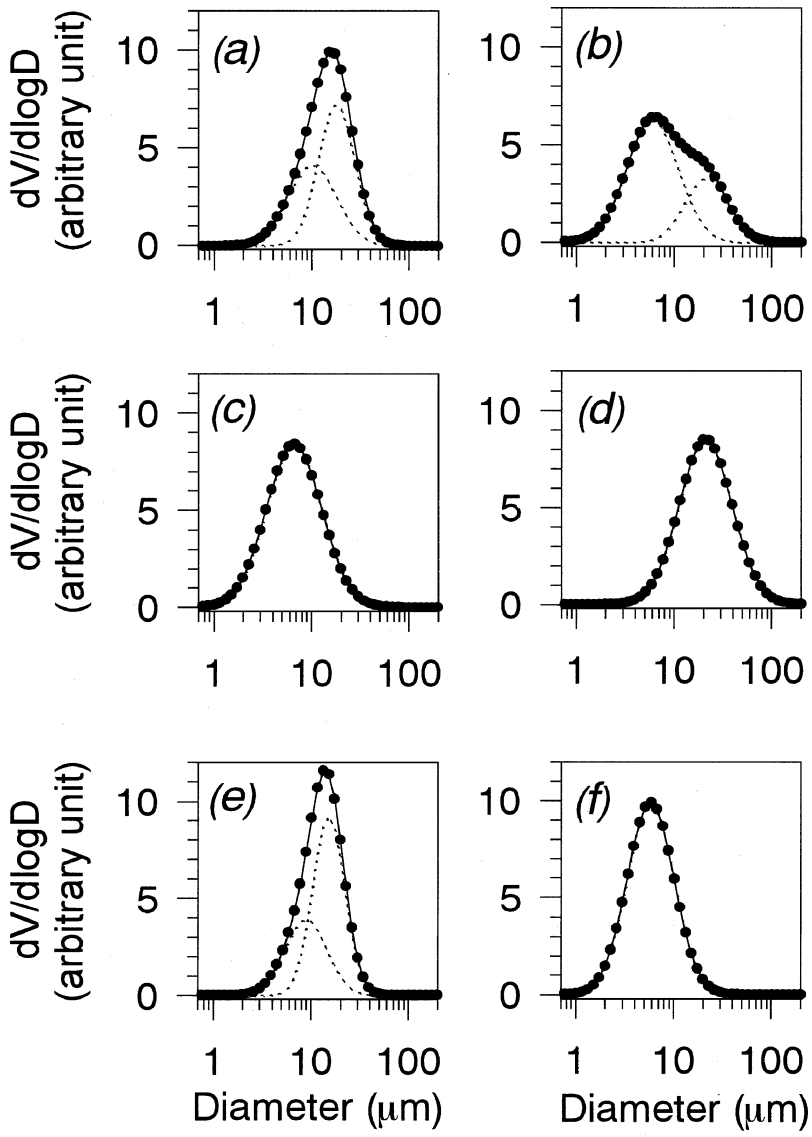

Fig 6. Volume size distribution of dust particles in the snow layer (a)–(f) shown in Fig. 5. Filled circles represent measured data points. Dotted lines in (a), (b) and (e) indicate bi-modal substructures obtained by lognormal fitting.

Table 2. Summary of amount of dust deposition at Murododaira, Mount Tateyama, Japan

Date of pit work	Water equivalent height (cm)	Cumulative dust (g m^{-2})
28 April 1997	299	4.3
21 March 1998	232	2.9
24 March 1999	288	7.4
21 April 2000	357	11.0
27 March 2001	264	11.2
26 March 2002	359	9.4

on average) at MR differs by a factor of about four during the 6 yr. Not including peaks of dust concentration in the profile, the amount of the dust deposition is small, as seen in 1998 (2.9 g m^{-2}). Without "red snow" events, Mount Tateyama receives no appreciable amount of dust, even though the orographic effect brings heavy snowfall at MR. This implies, again, the importance of wet deposition as "red snow" at the site.

The frequency of Kosa phenomena and the combination with snowfall varies greatly from year to year. Although the duration of snow accumulation from the bottom to the sampling date is irregular, the amount of dust deposition is considered an approximate deposition flux for the half year from winter to spring. Results from sea sediment are long-term averages—5–10 g m^{-2} yr^{-1} for the West Pacific (Rea and Leinen, 1988) and 15 g m^{-2} yr^{-1} for the Sea of Japan, Masuzawa et al. (1989)—that are inferred to be free from local soil and river contributions. As a multiyear average excluding the sand fraction in the deposits, 10 g m^{-2} yr^{-1} of dust flux was measured at Yashiro in Hyogo prefecture, western Japan (Inoue and Naruse, 1987). These annual fluxes are quite close to the average dust deposition flux

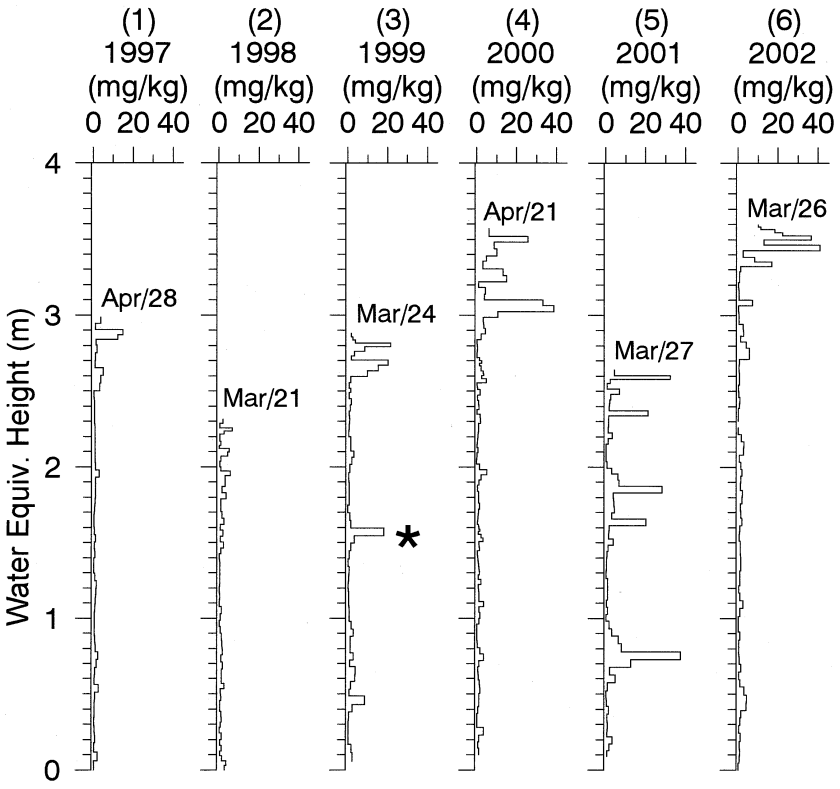

Fig 7. Vertical profiles of dust concentration (mg kg^{-1}) in the snow cover at MR from 1997 to 2002. The asterisk in 1999 represents the dust layer formed in late January as discussed in Section 3.1. The date of sampling is shown at the top of the dust profiles.

(7.7 g m^{-2} for winter to spring) at MR, implying that dusty precipitation in and near Japan contributes markedly to annual deposition of aeolian mineral dusts, especially in spring.

4. Summary and conclusions

Deposition of water-insoluble dust particles in the snow cover at Mount Tateyama, central Japan, was investigated for its formation process, characteristics and variation in amount deposited. Comparison of the temporal variations of aerosols in the free troposphere with snow height increments suggests that wet deposition of atmospheric supermicron aerosols dominates dust deposition and the thicker dust layer formation of the snow cover at Mount Tateyama. Dust layers in the snow cover contain Ca-rich materials that are found typically in Kosa dust particles. Volume size distributions of dust particles in the snow showed mono- and bi-modal structures having a volume median diameter of 6–21 μm. Dust concentrations in the snow cover over the last 6 yr at the site revealed sporadic high concentrations, frequently in spring, and large year-to-year variations in the amount deposited from winter to spring. The amount deposited ranged from 3–11 g m^{-2} at Murododaira. The average amount of dust deposited (7.7 g m^{-2}) for winter to spring at Murododaira was similar to the long-term averages in the existing literature, implying that dusty precipitation in spring is an important component of the annual deposition of aeolian mineral dust in the northwest Pacific region.

5. Acknowledgments

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