Tellus (2004), 56B, 85–92
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Lead-210 profile in firn layer over Antarctic ice sheet and its relation to the snow accumulation environment

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(Manuscript received 4 February 2003; in final form 12 August 2003)

ABSTRACT

Vertical distributions of ^{210}Pb in surface firn were obtained at five locations in east Dronning Maud Land, Antarctica. The distributions obtained in the inland high-plateau region are well described by the theoretical radioactive decay curve. On the other hand, the distributions obtained in the katabatic wind region have significant fluctuations including intervals where higher activity is found below layers with lower activity. We examined the relationship between the fluctuation of the ^{210}Pb profile and the temporal variation of the snow accumulation rate obtained by the snow stake method, and found a clear negative correlation between them. This result suggests that the fluctuation of the ^{210}Pb profile in the firn layer is closely related to the environment in the ice sheet surface, i.e. the extent of erosion–redistribution of snow. The measurement of the ^{210}Pb distribution in the ice sheet will be useful as an indicator of the surface stability in the Antarctic ice sheet.

1. Introduction

To study the snow accumulation rate is one of the basic requisites for understanding the surface mass balance on the Antarctic ice sheet (Goodwin, 1990; Gallée 2001). The ^{210}Pb (half-life of 22.3 yr) method of dating on a time scale of 100–200 yr proposed by Goldberg (1963), has been widely used to estimate the accumulation rate of surface snow over the Antarctic ice sheet (Crozaz et al. 1964; Picciotto et al. 1971; Nijampurkar and Rao, 1993; Bettoli et al. 1998). In the ^{210}Pb dating method described elsewhere (Faure, 1986; Suzuki et al. 1991, 1996), the accumulation rate of firn can be estimated from the depth profile of the activity of $^{210}Pb_{unsupported}$, which is only supplied by the radioactive decay of the atmospheric ^{222}Rn (half-life of 3.82 d). The activity of $^{210}Pb_{unsupported}$ can be obtained by subtracting the activity of the ^{210}Pb provided from ^{226}Ra (half-life of 1620 yr) in mineral particles ($^{210}Pb_{supported}$) from the total activity of ^{210}Pb in the firn. If the depth profile of ^{210}Pb is deep enough that the ^{210}Pb activity becomes constant, the constant value is usually considered as the activity of $^{210}Pb_{supported}$. The accumulation rate can be determined from the slope of the vertical distribution of $^{210}Pb_{unsupported}$ in firn, provided that the following assumptions are satisfied. First, the atmospheric flux of ^{210}Pb at the place of interest is nearly constant. Secondly, each firn layer behaves as a closed system for ^{210}Pb since the time of deposition. It is well known that the snow on the ice sheet surface is eroded and redistributed by severe katabatic winds in the inland region of Antarctica (Watanabe, 1978; Goodwin, 1990; Furukawa et al. 1996). If the assumptions described above are not satisfied at the surface of the Antarctic ice sheet, the ^{210}Pb method cannot be applied to estimate the snow accumulation rate. We measured the vertical distribution of ^{210}Pb in the firn layer in the inland region of Antarctica and examined its relationship to the instability of the snow accumulation rate obtained by the snow stake method.

The Japanese Antarctic Research Expeditions (JARE) have conducted many glaciological observations in east Dronning Maud Land, Antarctica over the past several decades (Watanabe, 1978; Ageta et al. 1989; Kamiyama et al. 1996; Dome-F Deep Coring Group, 1998). The study route from the coast to the Dome Fuji Station, 1000-km inland, has been established through these observations. Samples and snow stake data used in this study were obtained by the JARE expeditions along this study route.

2. Samples and methods

Firn samples for ^{210}Pb analysis were obtained by the 33rd JARE (1991–1993) during the period of their traverse, 15 November–20 December, 1992, from DF80, close to the Dome Fuji Station, to the Syowa Station (Fig. 1). Approximately 10-m length of firn

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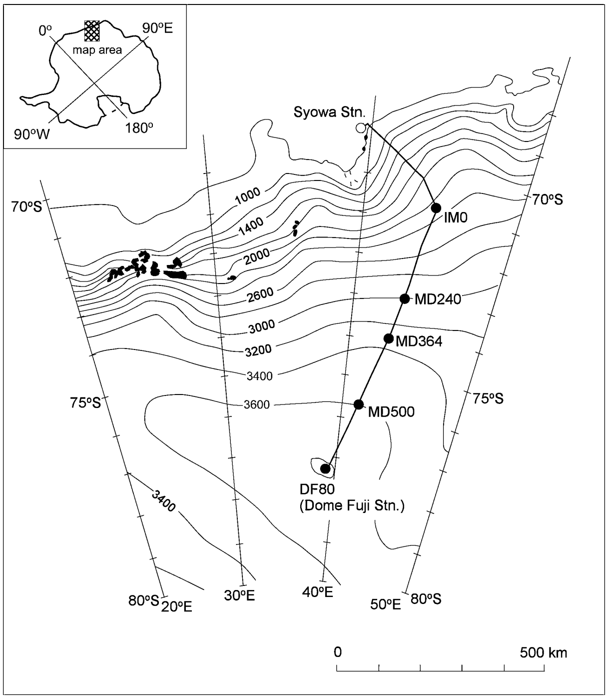

Fig 1. Map showing the study route between Syowa Station and DF80 in east Dronning Maud Land, Antarctica. Solid circles express the locations for snow sampling and snow stake measurement.

cores were collected in five locations, DF80 (77°23′S, 39°37′E, 3.8 km a.s.l.), MD500 (75°14′S, 42°01′E, 3.6 km a.s.l.), MD364 (74°01′S, 43°00′E, 3.4 km a.s.l.), MD240 (72°54′S, 43°29′E, 3.0 km a.s.l.) and IM0 (70°43′S, 44°17′E, 2.2 km a.s.l.), along the study route. The sampling dates at each location were 12, 24, 30 November, 4 and 13 December, 1992, respectively. The core sampling was performed in the research area, windward of the route, using a hand-operated ice auger. The core samples were cut into approximately 50-cm length, and then lapped with aluminum foil and sealed in polyethylene bag. The samples were transported in the atmosphere below −20 °C and they were stored in a −20 °C cold room at the National Institute of Polar Research. In 1998, the specific activities of ^{210}Pb in the samples were measured in approximately 0.5–1 m depth intervals by counting α-rays from ^{210}Po (half-life of 138 d), the granddaughter of ^{210}Pb. Details of sample preparation and counting apparatus were described in Suzuki et al. (1996). Snow stake measurements were conducted from 1985 to 1998 along the study route to measure the net amount of snow accumulation on the ice sheet (Kamiyama et al. 1994; Motoyama et al. 1995; Motoyama et al. 1999; Shiraiwa et al. 1996; Azuma et al. 1997).

3. Results and discussion

Depth profiles of ^{210}Pb in the firn cores collected at five locations in this study are shown in Fig. 2. The specific activities of ^{210}Pb are expressed as the value at the date of coring and the depth is expressed as the water equivalent. The ^{210}Pb activities in firn layers mostly decrease with depth at all locations. However, there are some clear reversals in the depth profiles. For instance, the activities in the upper two layers at MD240 are lower than that in the third layer. The irregularities may be due to a change of ^{210}Pb flux to the ice sheet and/or a post-depositional migration of snow together with the erosion–redistribution process of the ice sheet. If the old snow that eroded somewhere is transported by katabatic winds and is deposited on the fresh snow surface, irregularities in the ^{210}Pb profile will be expected.

To assess the fluctuation of the ^{210}Pb profile, we performed a regression analysis between the activity of ^{210}Pb and the snow depth. The regression curve, the equation and the square of correlation coefficient in Fig. 2 were obtained by a least-squares method on the assumption that the depth profile of ^{210}Pb should obey the theoretical radioactive decay scheme. The square of correlation coefficients of the statistical best-fitting curves are significant in order of 0.92 at DF80, 0.75 at MD500, 0.68 at IM0, 0.58 at MD240 and 0.38 at MD364. The result indicates that the vertical distribution of ^{210}Pb at DF80 has the smallest fluctuation of all the locations. On the other hand, the distribution at MD364 has the largest fluctuation. This result indicates that the sedimentation process of atmospheric ^{210}Pb in MD364 is not as stable as in DF80. In other words, the result indicates that the atmospheric flux of ^{210}Pb seems to be relatively constant at DF80, and/or the redistribution of surface snow may be insignificant at DF80.

Furukawa et al. (1996) divided the study route into three sections based on the regional characteristics of the snow surface features: a coastal region (0.6–2.0 km a.s.l.) characterized by a high frequency of small sastrugi and a low frequency of dunes; a katabatic wind region (2.0–3.6 km a.s.l.) characterized by the coexistence of small and large sastrugi, dunes and a glazed surface; and an inland plateau region (3.6–3.8 km a.s.l.) characterized by low frequencies of small sastrugi and dunes. Each section was also defined as a uniform accumulation zone by offshore cyclones, a sporadic accumulation zone with katabatic winds and a calm accumulation zone with weak winds, respectively. According to the above division, DF80 is located in an inland plateau region, MD500 is located in a boundary between an inland plateau region and a katabatic wind region and the other stations are located in a katabatic wind region. The significance of fluctuation in the depth profile of ^{210}Pb obtained in this study may be closely related to the environment in the ice sheet surface described above. Namely, the activity of ^{210}Pb in firn at DF80, located in a calm accumulation zone above 3.6 km a.s.l., should decrease exponentially with depth because the atmospheric flux of ^{210}Pb may be nearly constant and the disturbance of the snow surface may be weak. On the other hand, the vertical distribution of ^{210}Pb at MD364, MD240 and IM0, located in a sporadic accumulation zone between 2.0 and 3.6 km a.s.l., might not be expected to smoothly decrease with depth because the

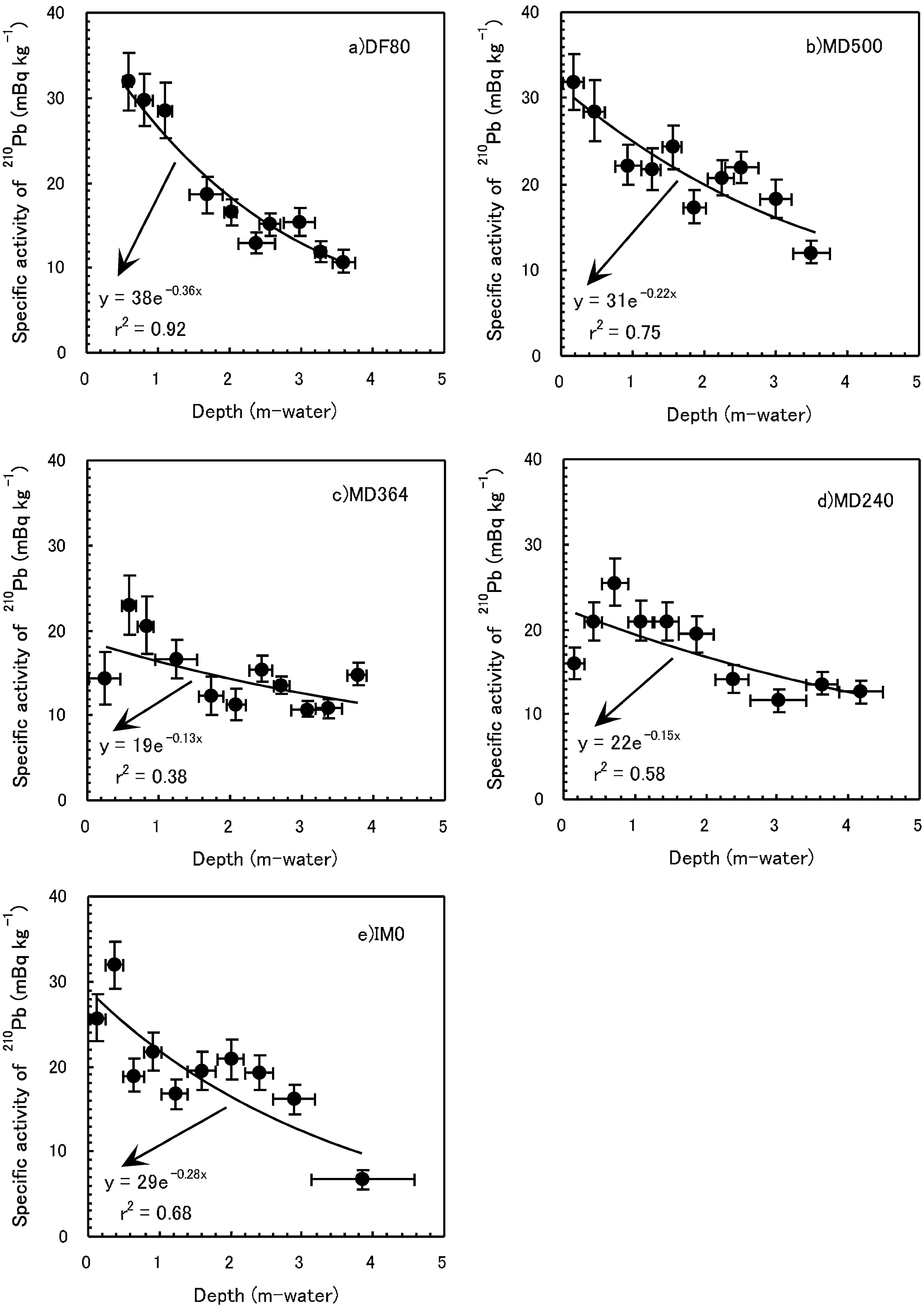

Fig 2. The depth profiles of the specific activities of ^{210}Pb in firn at (a) DF80, (b) MD500, (c) MD364, (d) MD240 and (e) IM0. The horizontal and vertical bars indicate the depth interval and the counting error (2σ), respectively. The solid curve in the figures is obtained by a least-squares method.

Table 1. Snow accumulation by stake method in east Dronning Maud Land, Antarctica

		Net accum. (cm snow)					Accum. Rate (cm snow yr^{-1})				
Duration	Days	DF80	MD500	MD364	MD240	IM0	DF80	MD500	MD364	MD240	IM0
27 Nov. 85–7 Nov. 92[a]	2538	60.0	–	–	–	–	8.6	–	–	–	–
27 Oct. 91–21 Jan. 92[a]	86	–	–	−1.0	−3.0	–	–	–	−4.2	−12.7	–
21 Jan. 92–10 Oct. 92[a]	263	–	–	−1.0	0.0	–	–	–	−1.4	0.0	–
10 Oct. 92–22 Jan. 93[a]	104	–	–	−1.0	10.0	–	–	–	−3.5	35.1	–
16 Oct. 92–13 Nov. 93[b]	393	–	13.0	0.0	51.0	–	–	12.1	0.0	47.4	–
15 Nov. 92–26 Nov. 93[b]	376	15.5	–	–	–	–	15.0	–	–	–	–
13 Nov. 93–17 Jan. 94[b]	65	–	−2.0	−1.0	7.0	−3.0	–	−11.2	−5.6	39.3	−16.8
26 Nov. 93–6 Jan. 94[b]	41	0.8	–	–	–	–	7.1	–	–	–	–
6 Jan. 94–19 Jan. 95[c]	379	7.7	–	–	–	–	7.4	–	–	–	–
17 Jan. 94–13 Sep. 94[c]	239	–	–	–	0.0	18.0	–	–	–	0.0	27.5
13 Sep. 94–17 Nov. 94[c]	65	–	–	–	5.0	5.0	–	–	–	28.1	28.1
17 Jan. 94–17 Nov. 94[c]	304	–	23.0	6.0	–	–	–	27.6	7.2	–	–
17 Nov. 94–28 Jan. 95[c]	72	–	0.0	−3.0	0.0	12.0	–	0.0	−15.2	0.0	60.8
19 Jan. 95–23 Jan. 96[d]	369	9.3	–	–	–	–	9.2	–	–	–	–
28 Jan. 95–14 Nov. 95[d]	290	–	3.5	12.5	−1.0	−6.0	–	4.4	15.7	−1.3	−7.6
14 Nov. 95–6 Jan. 96[d]	53	–	−0.5	−0.5	0.0	−0.5	–	−3.4	−3.4	0.0	−3.4
6 Jan. 96–29 Jan. 96[d]	24	–	2.5	−1.0	−0.5	–	–	38.0	−15.2	−7.6	–
27 Nov. 85–24 Nov. 97[e]	4381	66	–	–	–	–	5.5	–	–	–	–
6 Jan. 96–13 Jan. 97[e]	374	–	20.0	2.0	−1.0	4.0	–	19.5	2.0	−1.0	−3.9
13 Jan. 97–20 Oct. 97[e]	280	–	4.0	0.0	−3.0	–	–	5.2	0.0	−3.9	–
20 Jan. 97–15 Jan. 98[e]	360	6.9	–	–	–	–	7.0	–	–	–	–
Average							8.6	10.2	−2.0	9.5	13.2
Standard deviation							3.1	15.7	8.5	20.2	27.1
Coefficient of variation (%)							36	153	430	212	205

Notes: Superscripts a–e in duration indicate the data were cited from Kamiyama et al. (1994), Motoyama et al. (1995), Shiraiwa et al. (1996), Azuma et al. (1997) and Motoyama et al. (1999), respectively. Dashes indicate that the data were not available.

atmospheric flux of ^{210}Pb and the snow surface may be disturbed by severe katabatic winds. The result obtained at MD500 indicates that the location is placed in a transitional zone between a calm accumulation zone and a sporadic accumulation zone.

The results of snow stake measurement from 1985 to 1998 are reported in Table 1. Calculated annual accumulation rates are also listed in Table 1. The arithmetic means and their standard deviations (1σ) of the accumulation rates were 8.6 ± 3.1 cm snow yr^{-1} at DF80, 10.2 ± 15.7 cm snow yr^{-1} at MD500, -2.0 ± 8.5 cm snow yr^{-1} at MD364, 9.5 ± 20.2 cm snow yr^{-1} at MD240 and 13.2 ± 27.1 cm snow yr^{-1} at IM0. The coefficients of variation at each location were 36, 153, 430, 212 and 205, respectively. Similar to the vertical distribution of ^{210}Pb, the fluctuation of the accumulation rate obtained by the snow stake method at DF80 was the smallest of all the locations. A negative mean accumulation rate and maximum interannual variations were observed at MD364. The result coincides with the fact that MD364, MD240 and IM0 are situated in a katabatic wind region where the surface of the ice sheet would be disturbed by erosion and sporadic deposition processes. The relationship between the coefficient of variation (CV) in the snow stake measurement and the correlation coefficient (r^2) in the vertical distribution of ^{210}Pb is shown in Fig. 3. There is a clear negative correlation ($r^2 = 0.94$) between these two values. This suggests that the fluctuation of the depth profile of ^{210}Pb depends significantly on the instability of the snow accumulation rate on the ice sheet. The result also indicates that the atmospheric flux of ^{210}Pb on the ice sheet should be relatively constant in a place of moderate snow accumulation and that the ^{210}Pb in the firn layer should be well preserved in a calm accumulation zone with weak winds.

As described in the introduction, the accumulation rate of firn can be determined from the slope of the depth profile of $^{210}Pb_{unsupported}$. The activity of $^{210}Pb_{unsupported}$ should decrease as a function of time at a rate controlled by its half-life. The time elapsed since the deposition of a sample at a depth of z below the surface can be calculated from its activity of $^{210}Pb_{unsupported}$, provided that the initial activity of this nuclide has remained constant:

$$A_z = A_0 e^{-\lambda t}, \tag{1}$$

where A_z is the activity of $^{210}Pb_{unsupported}$ at a depth of z; A_0 is the activity of $^{210}Pb_{unsupported}$ at the surface ($z = 0$); λ is the decay constant of ^{210}Pb (3.11×10^{-2} yr^{-1}); and t is the age of the sample.

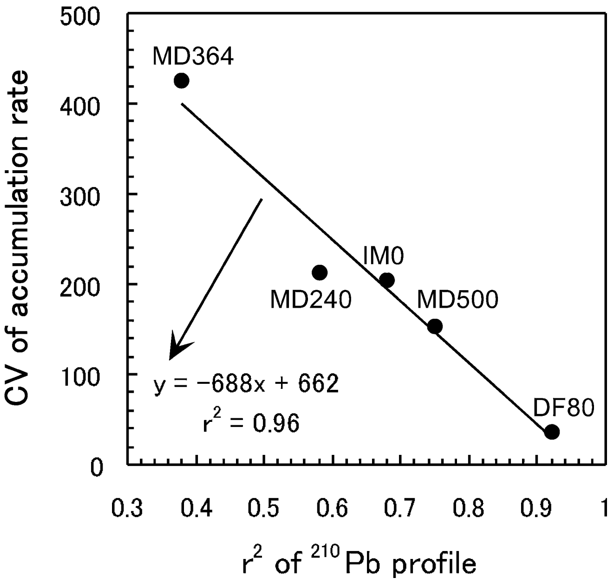

Fig 3. Relationship between the square of correlation coefficient (r^2) in the ^{210}Pb profile and the coefficient of variation (cv) of the snow accumulation rate obtained by the snow stake method. The solid line in the figure is obtained by a least-squares method.

When the rate of snow accumulation is constant, such that $a = z/t$, where a is the rate of accumulation,

$$\ln A_z = -z\lambda/a + \ln A_0. \qquad (2)$$

This is the equation of the straight line in coordinates of ln A_z and z, for which the slope is $-\lambda/a$ and the intercept on the ordinate axis is ln A_0. Thus, the accumulation rate a can be calculated from the slope. Unfortunately, our cores were not deep enough to obtain the activity of $^{210}Pb_{unsupported}$. Crozaz et al. (1964) reported that the ^{210}Pb activity at the Base Roi Baudouin (70°26′S, 24°19′E) was 12.5 mBq kg $^{-1}$ at 4.1–6.7 m depth in water equivalent and was 1.7 mBq kg^{-1} at the bottom of the core, 76–86 m depth in water equivalent. Sanak and Lambert, (1977) also reported that the activity at the South Pole was about 8 mBq kg^{-1} at 4-m depth in water equivalent and was about 1.5 mBq kg^{-1} at a bottom of core, 8-m depth in water equivalent. In the Greenland, the activity found at 40–51 m water depth in the Camp Century was 0.8 mBq kg^{-1} (Crozaz and Langway, 1966) and at approximately 80 m ice depth in Site D was about 1 mBq kg^{-1} (Dibb and Clausen, 1997). Our results of the ^{210}Pb activities in the deepest samples, 4-m depth in water equivalent, are ranged from 6.70 mBq kg^{-1} at IM0 to 14.8 mBq kg^{-1} at MD364 (Fig. 2) and are comparable to values obtained previously at the similar depth of the Antarctic firn layer (Crozaz et al. 1964; Sanak and Lambert, 1977). However, they are approximately one order of magnitude larger than the activities in the deepest samples of previous studies. This result indicates that the activities in the deepest samples obtained in this study cannot be considered as the activity of $^{210}Pb_{supported}$. We assumed the activity of $^{210}Pb_{supported}$ at all location in this study is 1 mBq kg^{-1} and calculated the activity of $^{210}Pb_{unsupported}$.

Plots of the natural logarithm of the $^{210}Pb_{unsupported}$ activity (ln A_z) that is obtained based on above assumption versus the depth in water equivalent (z) are shown in Fig. 4. The straight line and its equation in the figure were obtained by a least-squares method. Estimated accumulation rates were 8.1 cm water yr^{-1} at DF80, 13 cm water yr^{-1} at MD500, 22 cm water yr^{-1} at MD364, 20 cm water yr^{-1} at MD240 and 10 cm water yr^{-1} at IM0, respectively. The density of firn samples used in this study ranged from 0.3 to 0.5 g cm^{-3}. Using the average value, 0.4 g cm^{-3}, the accumulation rates as snow are estimated to be 20 cm snow yr^{-1} at DF80, 33 cm snow yr^{-1} at MD500, 55 cm snow yr^{-1} at MD364, 50 cm snow yr^{-1} at MD240 and 25 cm snow yr^{-1} at IM0. The ^{210}Pb-based estimate of snow accumulation rate are 1.9–5.3 times larger than the rate obtained by the snow stake method (Table 1). The snow accumulation rate at the Dome Fuji station, close to DF80, was estimated by various methods, snow stake method, fission-product tracer analysis, electrical conductivity measurement and artificial radioactivity analysis. Each of these methods suggests a similar accumulation rate of ∼3 cm water yr^{-1} for the Holocene period (Dome-F Ice Core Research Group, 1998). Although we cannot wholly explain this disagreement, we suppose that the disagreement may be due to instability of the ^{210}Pb profile and/or systematic decrease of the atmospheric ^{210}Pb flux over the past one to two centuries (Sanak and Lambert, 1977), Nijampurkar and Clausen, 1990; Dibb and Clausen, 1997). Dibb and Clausen (1997) reported the ^{210}Pb chronology for Site D, Greenland yields ages that are significantly younger (the accumulation rate is too high) than the age based on annual layer counting. They also concluded that the ^{210}Pb flux over Greenland appears to have steadily decreased throughout the present century and that the decrease is reflecting an increasing marine influence on air masses over the Greenland ice sheet. The decreasing of ^{222}Rn emanation and volcanic activities, and the increasing of aerosol scavenging efficiency in this, warm and geologically quiet, century may be other possible causes for the global scale decline of atmospheric ^{210}Pb flux. The result obtained in this study suggests that the decline of the atmospheric ^{210}Pb flux may occur not only in the Greenland ice sheet but also in the Antarctic ice sheet.

The specific activity of ^{210}Pb in the top core from DF80 was 31.9 mBq kg^{-1} (Fig. 2a). We can estimate the deposition flux of ^{210}Pb in DF80 at the present time by multiplying the specific activity and the average accumulation rate, 0.086 m snow yr^{-1} (Table 1), and the average surface snow density, 300 kg m^{-3} (Azuma et al. 1997) in DF80. The calculated deposition flux is approximately 820 mBq m^{-2} yr^{-1}. This value may be an underestimate because the specific activity of ^{210}Pb in the surface snow would be much higher than that in the depth of the top core, 0.52–0.95 m. At any rate, the flux is comparable to 900 mBq m^{-2} yr^{-1} obtained in an inland location, 82.1°S, 55.1°E, 3720 m a.s.l.,

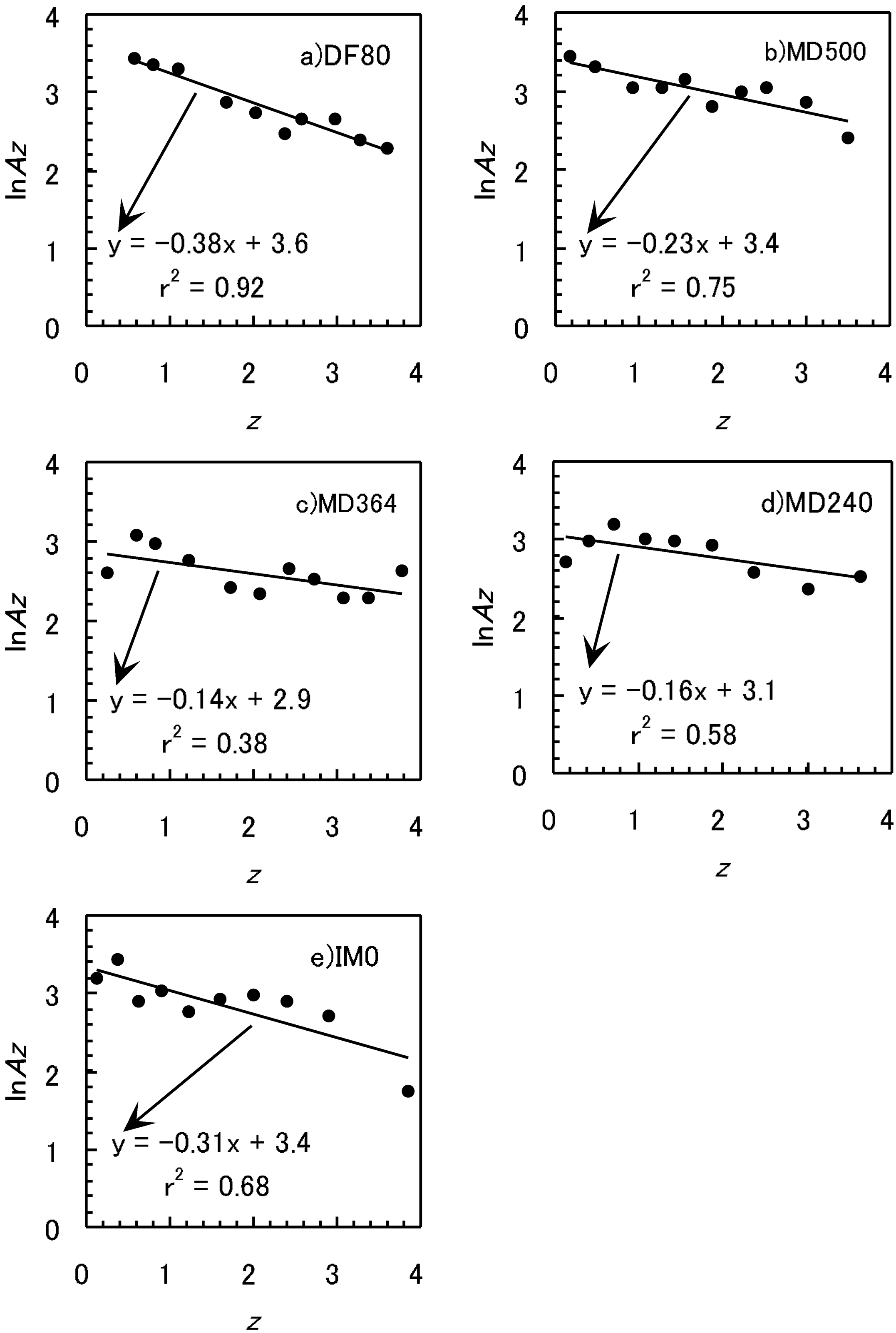

Fig 4. Plots of the natural logarithm of the $^{210}Pb_{unsupported}$ activity ($\ln A_z$) versus the depth in water equivalent (z) at (a) DF80, (b) MD500, (c) MD364, (d) MD240 and (e) IM0. The straight line in each figure was obtained by a least-squares method.

and one order of magnitude smaller than the value, 8200 mBq m^{-2} yr^{-1}, obtained in a coastal location, 70.4°S, 24.3°E, 20 m a.s.l., in east Dronning Maud Land (Pourchet et al. 1997).

4. Conclusions

Depth profiles of ^{210}Pb in the surface firn at five locations in east Dronning Maud Land, Antarctica were obtained. The correlation coefficients of the statistical best-fitting curve for the profiles were significant in order of DF80, MD500, IM0, MD240 and MD364. We examined the relationship among the correlation coefficients and the coefficients of variation of the snow accumulation rate, and found a clear negative correlation between these two values. These results suggest that the atmospheric ^{210}Pb in an inland plateau above 3.6 km a.s.l. deposit sequentially during calm winds, and that the accumulation of ^{210}Pb on the snow surface in a sporadic accumulation zone between 2.0 and 3.6 km a.s.l., is largely disturbed by strong katabatic winds. The results revealed that the fluctuation of the depth profile of ^{210}Pb clearly depend on the variability of snow accumulation. Therefore, the measurement of ^{210}Pb distribution in the ice sheet will be useful as an indicator of the surface stability in the Antarctic ice sheet. The depth profile of ^{210}Pb at DF80 seems sufficiently structured for the ^{210}Pb dating because it has the smallest fluctuation of all the location in this study. However, the ^{210}Pb-based snow accumulation rate at DF80, 8.1 cm water yr^{-1}, was approximately twice as large as the value obtained by snow stake method. This result supports an occurrence of the systematic decline of the atmospheric ^{210}Pb flux over the past 200 yr suggested by previous studies (Sanak and Lambert, 1977; Nijampurkar and Clausen, 1990; Dibb and Clausen, 1997).

5. Acknowledgments

We would like to thank the members of the 33rd Japanese Antarctic Research Expedition, conducted by Professor M. Fukuchi of the National Institute of Polar Research, for their support in the field operations. The reviewers provided helpful suggestions for improving the earlier version of this manuscript.

References

Ageta, Y., Kamiyama, K., Okuhira, F. and Fujii, Y. 1989. Geomorphological and glaciological aspects around the highest dome in Queen Maud Land. East Antarctica. *Proc. NIPR Symp. Polar Meteorol. Glaciol.* **2**, 88–96.

Azuma, N., Kameda, T., Nakayama, Y., Tanaka, Y., Yoshimi, H., Furukawa, T. and Ageta, Y. 1997. Glaciological data collected by the 36th Japanese Antarctic Research Expedition during 1995–1996. In: *JARE Data Rep.*, National Institute of Polar Research, Tokyo. 223.

Bettoli, M. G., Cantelli, L., Quarin, D., Ravanelli, M., Tositti, L. and Tubertini, O. 1998. Marine sediments and snow from Ross Sea region (Antarctica) dating by ^{210}Pb method. *Int. J. Environ. Anal. Chem.* **71**, 321–330.

Crozaz, G. and Langway, C. C. Jr, 1966. Dating Greenland firn-ice cores with Pb-210. *Earth Planet. Sci. Lett.* **1**, 194–196.

Crozaz, G., Picciotto, E. and De Breuck, W. 1964. Antarctic snow chronology with Pb^{210}. *J. Geophys. Res.* **69**, 2597–2604.

Dibb, J. E. and Clausen, H. B. 1997. A 200-year ^{210}Pb record from Greenland. *J. Geophys. Res.* **102**, 4325–4332.

Dome-F Deep Coring Group. 1998. Deep ice-core drilling at Dome Fuji and glaciological studies in east Dronning Maud Land, Antarctica. *Ann. Glaciol.* **27**, 333–337.

Dome-F Ice Core Research Group. 1998. Preliminary investigation of palaeoclimate signals recorded in the ice core from Dome Fuji station, east Dronning Maud Land, Antarctica. *Ann. Glaciol.* **27**, 338–342.

Faure, G. 1986. The U-series disequilibrium methods of dating. In: *Principles of Isotope Geology*. Wiley, New York, 363–385.

Furukawa, T., Kamiyama, K. and Maeno, H. 1996. Snow surface features along the traverse route from the coast to Dome Fuji Station, Queen Maud Land, Antarctica. *Proc. NIPR Symp. Polar Meteorol. Glaciol.* **10**, 13–24.

Gallée, H., Guyomarc′h, G. and Brun, E. 2001. Impact of snow drift on the Antarctic ice sheet surface mass balance: possible sensitivity to snow-surface properties. *Boundary-Layer Metorol.* **99**, 1–19.

Goldberg, E. D. 1963. Geochronology with lead-210. In: *Radioactive Dating*. International Atomic Energy Agency, Vienna, 121–131.

Goodwin, I. D. 1990. Snow accumulation and surface topography in the katabatic zone of Eastern Wilks Land, Antarctica. *Antarct. Sci.* **2**, 235–242.

Kamiyama, K., Furukawa, T., Maeno, H., Kishi, T. and Kanao, M. 1994. Glaciological data collected by the 33rd Japanese Antarctic Research Expedition in 1992. In: *JARE Data Rep.*, National Institute of Polar Research, Tokyo. 194.

Kamiyama, K., Motoyama, H., Fujii, Y. and Watanabe, O. 1996. Distribution of hydrogen peroxide in surface snow over Antarctic ice sheet. *Atmos. Environ.* **30**, 967–972.

Motoyama, H., Enomoto, H., Miyahara, M. and Koike, J. 1995. Glaciological data collected by the 34th Japanese Antarctic Research Expedition in 1993. In: *JARE Data Rep.*, National Institute of Polar Research, Tokyo. 202.

Motoyama, H., Kawamura, Y., Kanao, M., Hirasawa, N., Kaneto, S. and Yamanouchi, T. 1999. Glaciological data collected by the 38th Japanese Antarctic Research Expedition during 1997–1998. In: *JARE Data Rep.*, National Institute of Polar Research, Tokyo. 239.

Nijampurkar, V. N. and Clausen, H. B. 1990. A century old record of lead-210 fallout on the Greenland ice sheet. *Tellus* **42B**, 29–38.

Nijampurkar, V. N. and Rao, D. K. 1993. Polar fallout of radionuclides ^{32}Si, ^{7}Be and ^{210}Pb and past accumulation rate of ice at Indian station, Dakshin Gangotri, East Antarctica. *J. Environ. Radioactivity* **21**, 107–117.

Picciotto, E., Crozaz, G. and De Breuck, W. 1971. Accumulation on the South Pole-Queen Maud Land Traverse, 1964–1968. In: *Antarctic Snow and Ice Studies II* (ed.A. P. Crary). *Am. Geophys. Union*, Washington, DC, 257–315.

Pourchet, M., Bartarya, S. K., Maignan, M., Jouzel, J., Pinglot, J. F., Aristarain, A. J., Furdada, G., Kotlyakov, V. M., Mosley-Thompson, E., Preiss, N. and Young, N. W. 1997. Distribution and fall-out of ^{137}Cs and other radionuclides over Antarctica. *J. Glaciol.* **43**, 435–445.

Sanak, J. and Lambert, G. 1977. Lead 210 or climatic changes at South Pole?. *Geopys. Res. Lett.* **4**, 357–359.

Shiraiwa, T., Saito, T., Saito, T., Shoji, H., Taguchi, Y., Abo, T., Yamamoto, Y., Inagawa, Y., Yokoyama, K. and Watanabe, O. 1996. Glaciological data collected by the 35th Japanese Antarctic Research Expedition during 1994–1995. In: *JARE Data Rep.*, National Institute of Polar Research, Tokyo. 211.

Suzuki, T., Osada, K. and Fujii, Y. 1991. Dating of an ice core from the Hø ghetta ice dome in Spitsbergen by ^{210}Pb analysis. *Bull. Glacier Res.* **9**, 55–58.

Suzuki, T., Maki, A., Ohta, K., Kamiyama, K., Fujii, Y. and Watanabe, O. 1996. Determination of lead-210 in an ice core from an Arctic glacier by an alpha-ray measurement. *Anal. Sci.* **12**, 923–926.

Watanabe, O. 1978. Distribution of surface features of snow cover in Mizuho plateau. *Mem. Natl Inst. Polar Res., Spec. Issue* **7**, 44–62.