Polar Meteorol. Glaciol., **18**, 72–81, 2004

Periodicities of palaeo-climatic records extracted from the Dome Fuji deep core

Kazuhide Satow[1]*, Okitsugu Watanabe[2], Yoshiyuki Fujii[2], Kokichi Kamiyama[2],
Hideaki Motoyama[2], Teruo Furukawa[2], Makoto Igarashi[2] and Satoru Kanamori[3]

[1] *Nagaoka National College of Technology, 888, Nishi-katakai-machi, Nagaoka 940-8532*
[2] *National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*
[3] *Atmospheric and Hydrospheric Research Institute (emeritus), Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-0814*
**Corresponding author. E-mail: ksatow@nagaoka-ct.ac.jp*

(Received February 10, 2004; Accepted August 10, 2004)

Abstract: The Antarctic ice sheet preserves palaeo-climate information in the form of physical and chemical stratigraphy. A deep ice core was continuously drilled down to a depth of 2503 m at Dome Fuji Station, East Dronning Maud Land, Antarctica, during the 1993–97 JARE inland operations. A time scale for the Dome Fuji core is calculated from past accumulation rates and an ice flow model. A depth-age profile was obtained for the past 320 kyr back in time.

The obtained palaeo-temperature profile shows the past three glacial and interglacial periods. The power spectrum for oxygen isotope variation for 320 kyr shows three dominant cycles of 107 kyr, 40 kyr and 21 kyr. Each of these three cycles is similar to Milankovitch cycles. Moving-window spectrum analysis, using a 130 kyr window stepped by 10 kyr over the past 320 kyr, found these main cycles in every age.

Variations of other chemical concentrations were also recovered from the Dome Fuji ice core, and are inversely correlated to the temperature profile. Concentrations of terrestrial and marine origin substances are high in glacial periods, and low in interglacial periods. Over the past 320 kyr, the dominant periodicities of temperature were also detected in almost all chemical records.

key words: Dome Fuji, core, climatic record, Milankovitch cycle

1. Introduction

The Japanese Antarctic Research Expedition (JARE) has planned and executed the Dome Fuji Program, a comprehensive glaciological research program focusing on deep ice coring and analysis for retrieving past environmental information recorded in the Antarctic ice sheet. A continuous deep ice core down to a depth of 2503 m was recovered at Dome Fuji Station (Fig. 1), Dronning Maud Land, Antarctica (77° 19′01″S, 39° 42′12″E, elevation: 3810 m a.s.1., ice thickness: 3028 m, mean surface temperature: −57.3°C; Fujita *et al*., 1998) by using a JARE mechanical drill in a liquid-filled hole during the 1993–97 field operations (Dome-F Deep Coring Group, 1998). The core quality is excellent even in the slightly brittle zone ranging from 550 to 840 m depth.

Oxygen isotope measurements were conducted on 7 to 50 cm-long ice core samples

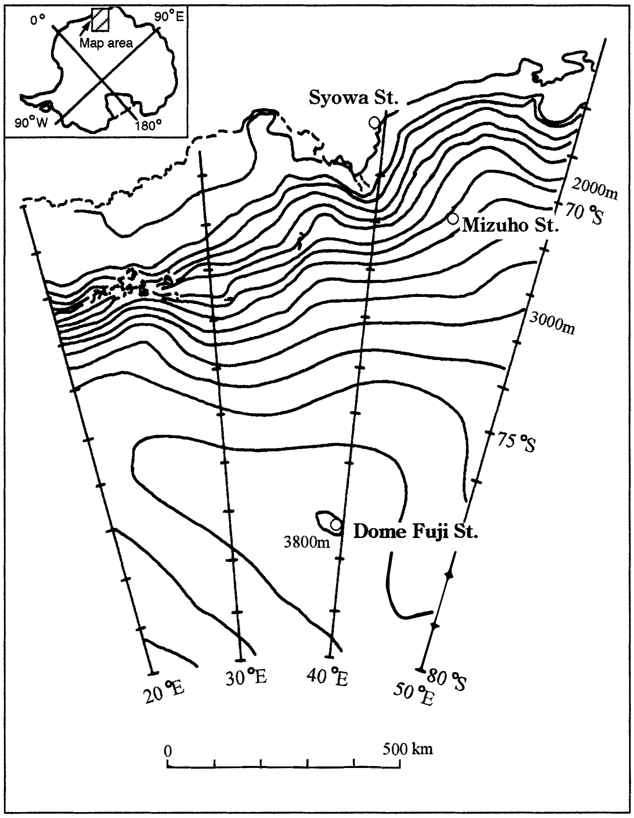

Fig. 1. Location of Dome Fuji Station.

selected from the entire core depth (Dome-F Ice Core Research Group, 1998). Several ice core dating methods have been devised and used for dating of cores (Lorius *et al.*, 1985; Jouzel *et al.*, 1993; Petit *et al.*, 1999; Parrenin *et al.*, 2001). Dating of the Dome Fuji core in this paper was performed by Watanabe *et al.* (2003). The procedure is as follows. A time scale for the Dome Fuji core is calculated from past accumulation rates and an ice flow model. Past accumulation rates were converted from oxygen isotope values by using an empirical equation obtained in the Dome Fuji area. A steady-state flow model was developed for a time scale calculation of the Summit ice core, Greenland. Compared with other Antarctic deep cores, the core used by this research is just from a dome summit, so there is little influence of ice flow, which is very advantageous to determine the age of an ice core. Reference depth points from volcanic signals and annual layer thickness values measured on the Dome Fuji core allowed for tuning of the calculated time scale. A depth-age profile was obtained for the past 320 kyr.

2. Analysis of variation of the oxygen isotope ratio

The δ^{18}O profile with the time scales obtained is shown in Fig. 2. The δ^{18}O profile clearly shows three glacial-interglacial cycles in a quite similar way to the Vostok δD profile (Jouzel *et al.*, 1996). The features of the δ^{18}O profile are as follows (Watanabe *et al.*, 2003).

The accumulation rate is small in a glacial period, and large in an interglacial period, correlating with the δ^{18}O profile. The paleo-temperature profile shows a variation of approximately 10°C between glacial and interglacial periods. The difference in temperature of 10°C between glacial and interglacial periods is similar to the temperature difference in the Greenland summit ice core (*e.g.*, Grootes *et al.*, 1993).

In the three long glacial periods, big changes of 4 to 6°C in the temperature are also seen. The temperature change among the glacial periods is very similar, especially between the last glacial period and the penultimate period. The highest temperature of the Holocene is 2 to 3°C lower than those of the previous interglacial periods. Each glacial period finishes with a sudden rise in temperature. Although the minimum

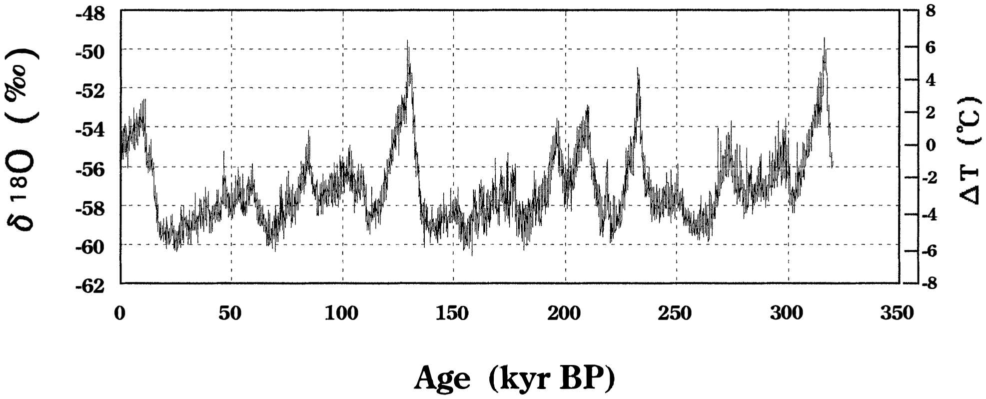

Fig. 2. δ^{18}O profile obtained from the Dome Fuji ice core. The temperature variation (ΔT) shows differences from the mean of present temperature.

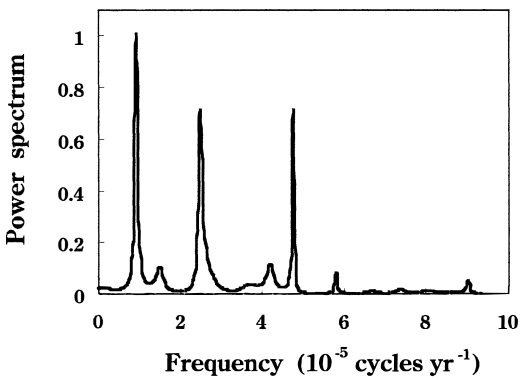

Fig. 3. Power spectrum of δ^{18}O variation for 320 kyr in the Dome Fuji ice core. The vertical-axis unit is arbitrary.

temperature occurs just before the end of the Wisconsin age, this is not the case in the other two glacial periods.

In order to detect periodicities of δ^{18}O variation of the Dome Fuji core over the past

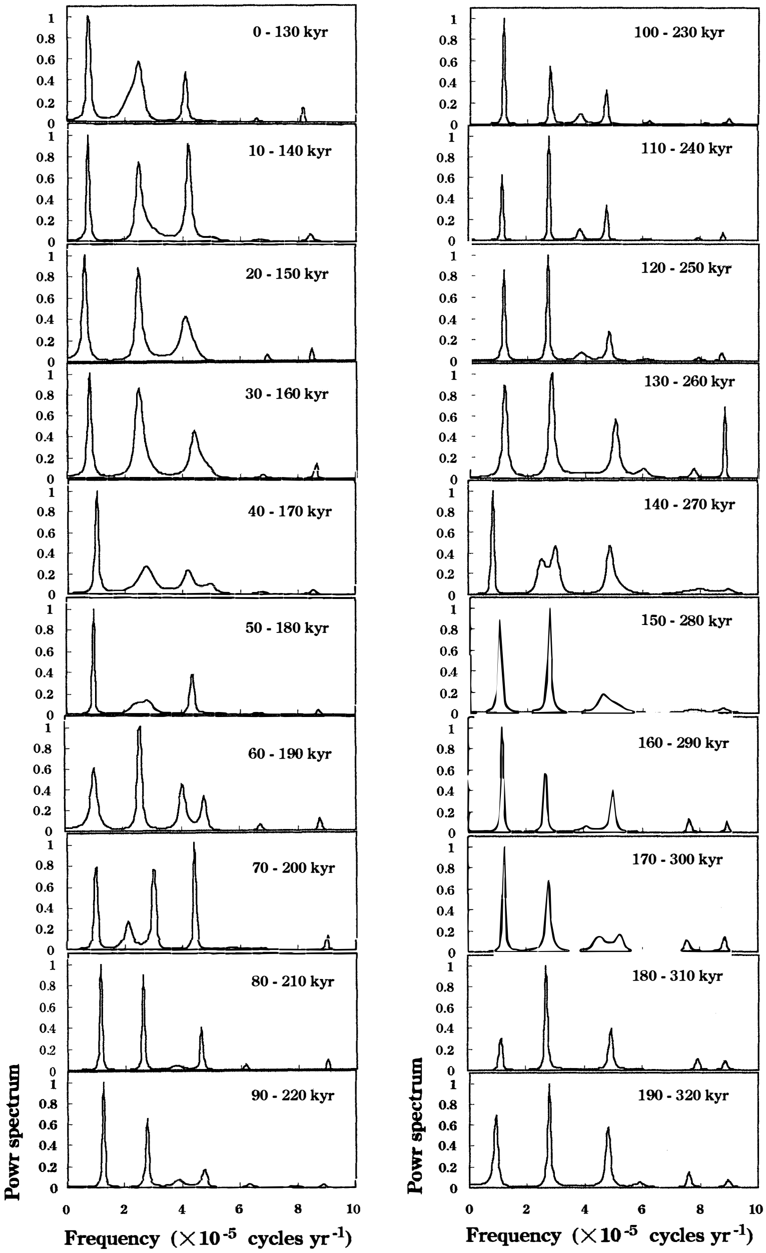

Fig. 4. Power spectrum of δ^{18}O variation for each 130 kyr in the Dome Fuji ice core. The vertical-axis unit is arbitrary.

320 kyr, power spectra were computed by applying the maximum entropy method (MEM) developed by J.P. Burg (Hino, 1977). The following are important features of the MEM. Spectral analysis is possible even when data length is shorter than the wavelength to be analyzed. The spectrum resolution is very high. The data are processed as follows. Oxygen data consisting of 6163 values were obtained from the 2503 m deep core. These data were interpolated every 500 years by the spline-fitting method. Using these 642 processed data, spectral analysis was performed on the deviations from the average value for 320 kyr. The treatment of the final prediction error in computing is based on Akaike's method (Akaike, 1969a, b). Thus we selected an order of the auto-regressive model M = 300 for the MEM spectrum and the spectral number Sn = 400 between the minimum frequency 0 and the maximum frequency 30 for 320 kyr. Figure 3 shows the spectral power versus the frequency. Three dominant periodicities are seen at 107 kyr, 40 kyr, and 21 kyr. These peaks are close to the three cycles predicted by the astronomical theory of Milankovitch, *i.e.* the cycles of eccentricity of the earth's orbit (100 kyr), obliquity of the earth's axis (41 kyr), and precession of the earth's axis (23 kyr and 19 kyr), respectively.

The δD (or isotopic temperature) variation in the 420 kyr Vostok ice core shows prominent cycles at 100 kyr and 41 kyr (Petit *et al.*, 1999; Muller and MacDonald, 2000). Analysis of the past 160 kyr of the Vostok ice core shows dominant periodicities of 116 kyr and 21 kyr in isotopic temperature (Jouzel *et al.*, 1987), and 108 kyr, 42 kyr and 25 kyr in CO_2 variation (Barnola *et al.*, 1987).

In order to examine the time-dependent spectral evolution in the Dome Fuji core, moving-window spectrum analysis using a 130 kyr window stepped by 10 kyr over the last 320 kyr was performed (Fig. 4). Auto regressive orders for the MEM spectrum were selected to be 150. Three to four dominant periodicities are seen in each 130 kyr window (Fig. 5); all are close to the three Milankovitch cycles. The amplitude of the 100 kyr cycle evolves over the length of the record. The exact frequencies of the 40 kyr and 20 kyr peaks vary slightly over time, possibly due to the uncertainties in the time

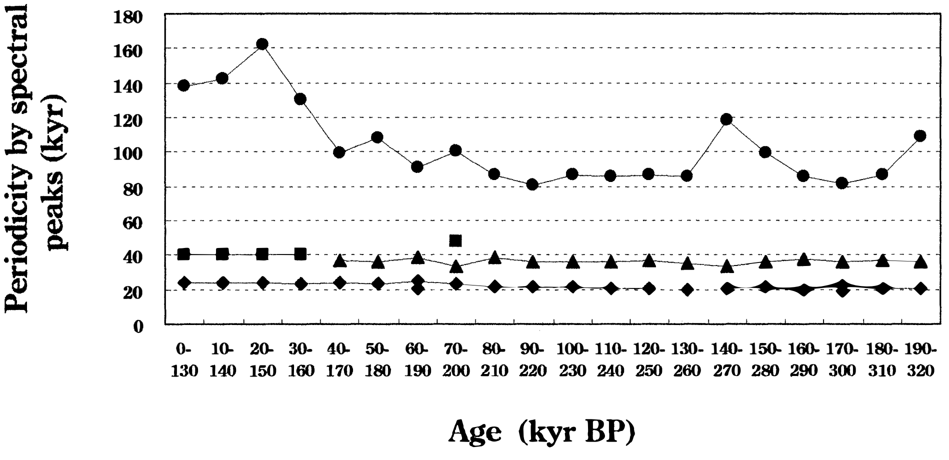

Fig. 5. Periodicity by spectral peaks of $\delta^{18}O$ for each 130 kyr in the Dome Fuji ice core.

scale and/or other causes. However, three dominant cycles are present throughout the record.

3. Analysis of variation of the major ion components

Variations in the concentrations of terrestrial and marine impurities in ice cores provide information on atmospheric circulation systems. Higher loading of terrestrial impurities is attributed to increased aridity and windiness over continental areas, while higher loading of marine-derived species is attributed to a combination of changes in biological productivity and increased wind speeds at the ocean surface. Basic analyses of terrestrial and marine impurities such as methanesulfonic acid (MSA) and major ion species: Cl^-, NO_3^-, SO_4^{2-}, Na^+, Mg^{2+} and Ca^{2+} etc. were performed on the Dome Fuji deep core in addition to $\delta^{18}O$ analysis. Variations in these concentrations are shown in Fig. 6, in addition to the Cl^-/Na^+ ratio and non-sea-salt sulfuric acid ion (nss-SO_4^{2-}) concentration. Variations of almost all impurities except the Cl^-/Na^+ ratio seem to be inversely correlated with the $\delta^{18}O$ variation. That is, the concentration of each impurity is high in a glacial period, and low in an interglacial period.

$\delta^{18}O$ as an index of temperature and Na^+ as an index of marine influence have high values in glacial periods and low values in interglacial periods. Although snow accumulation in glacials is about 30 to 50% of that in interglacial periods (Watanabe *et al.*, 2003), sea salt concentration in glacial periods 5 to 6 times higher than that in interglacial periods cannot be explained by accumulation changes alone. The transportation distance to Dome Fuji of Na^+ from an open ocean source must have been longer than at present, since sea ice covered a larger area in glacial periods. Considering that the amount of sea salt flux decreases exponentially with transportation distance, the increase in Na^+ concentration in glacial periods must be due to enhanced atmospheric circulation. Na^+ is predominantly derived from sea-salt, while Ca^{2+} is almost entirely of continental origin (De Angelis *et al.*, 1997; Legrand and Mayewski, 1997). The concentration of Ca^{2+} in glacials is 10 times or more of that in interglacials (Fig. 6). Thus a large quantity of terrestrial dust particles may have been conveyed to Antarctica from exposed continental shelves by lowering of sea surface level and strengthened atmospheric circulation. During glacial periods, the strengthened atmospheric circulation systems transported more continental and marine species to the ice sheet. For SO_4^{2-}, the marine component is most important, with biogenic sources being dominant over the sea-salt-derived component, but there are also terrestrial biogenic and volcanic sources (Legrand, 1995). Both SO_4^{2-} and nss-SO_4^{2-} show similar variations.

From analyses of snowfall and shallow snow layers at Dome Fuji (Iizuka *et al.*, 2002), the Cl^-/Na^+ ratio of snowfall is high in summer and low in winter, and these seasonal signals are preserved in snow layers from the surface to 3.4 m depth. Different changes from the seawater Cl^-/Na^+-value (1.18) are mainly due to changes in Cl^--concentration. But transport of sea salt from the ocean, deposition on the ice sheet and metamorphosis after deposition are still poorly understood. The variation of Cl^-/Na^+ ratios on glacial-interglacial timescales is similar to the $\delta^{18}O$-variation, that is, Cl^-/Na^+ is low in glacial periods and high in interglacial periods.

Fujii *et al.* (2002) analyzed MSA from marine biogenetic origins and dust concen-

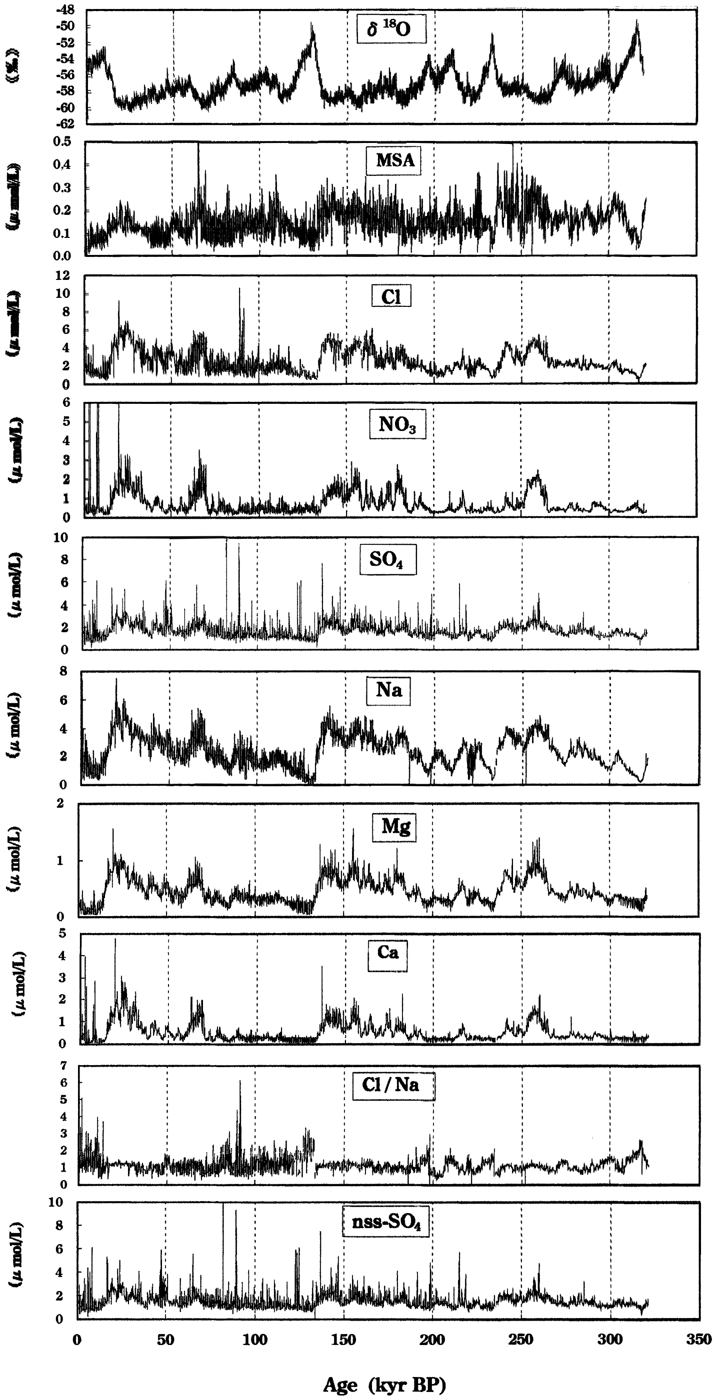

Fig. 6. Dome Fuji time series of $\delta^{18}O$*, MSA,* Cl^-*,* NO_3^-*,* SO_4^{2-}*,* Na^+*,* Mg^{2+}*,* Ca^{2+}*,* Cl^-/Na^+ *ratio and nss-*SO_4^{2-}*.*

tration in the Dome Fuji core, and reported the following. Analysis of $\delta^{18}O$, dust concentration and MSA shows that the increase of aeolian dust did not result in climate cooling and was not associated with MSA increase. The MSA peaks were accompanied by climate warming, suggesting that not dust but the thermohaline circulation in the sea seems to have played an important role in the biological pump.

Under the above mentioned background, spectral analyses of chemical variations were also carried out. Data processing was performed by the same method as in the case of $\delta^{18}O$. We selected an autoregressive order $M=250$–350 for the MEM spectrum. The analyses show clearly dominant periodicities (Fig. 7). They are summarized along $\delta^{18}O$ periodicities in Table 1. The dominant periodicities of marine Na^{+} and terrestrial Ca^{2+} are similar to those of $\delta^{18}O$. Almost all the chemical periodicities except for two periodicities for MSA show strikingly similar patterns. Although not shown here, the result of sea-salt-SO_4^{2-} showed the same periodicities.

These results suggest that the same process driving temperature variation has also affected the variation of chemical species, which are also synchronous with temperature.

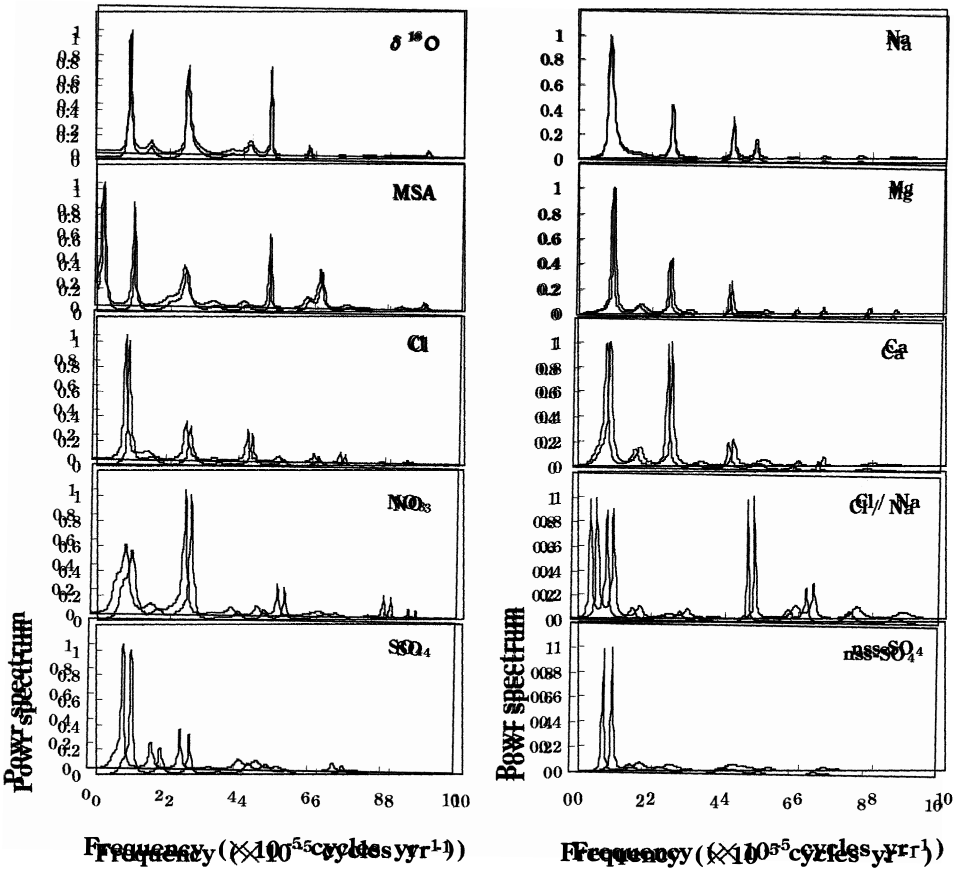

Fig. 7. Power spectrum of $\delta^{18}O$, MSA, Cl^{-}, NO_3^{-}, SO_4^{2-}, Na^{+}, Mg^{2+}, Ca^{2+}, Cl^{-}/Na^{+}- and nss-SO_4^{2-} variations for the 320 kyr in the Dome Fuji ice core. The vertical-axis unit is arbitrary.

Table 1. Periodicities (kyr) shown in spectral peaks. The parentheses show weak peaks with relative power spectrum below 0.2.

	periodicity (kyr)								
$\delta^{18}O$		107	(66)	40	(27)	(24)	21	(17)	
MSA	478	95		41	(31)	(25)	21	16	
Cl		112		39		24	(20)		
NO_3		104	(61)	39	(26)	(22)	19	(16)	
SO_4		104	57	40		(24)	(22)		(15)
Na		113		39		24	(21)		
Mg		103	(58)	39		24			
Ca		113	(59)	39	(30)	24	(20)		
Cl/Na	195	104	(60)	(41)	(34)		21	(17)	16
nss-SO_4		109	(60)	(40)		(24)	(19)		
mean		106	60	40		24	20		

Although such a causal relationship is as yet unknown, it is a future research subject. The meaning of other periodicities than the Milankovitch cycles is shown in Table 1.

4. Concluding remarks

Paleo-environmental records over the last 320 kyr in a 2503 m deep ice core were obtained at Dome Fuji Station. The variation of paleo-temperature shows three clear glacial-interglacial cycles over the past 320 kyr. Spectral analysis shows dominant periodicities of about 100 kyr, 40 kyr and 20 kyr, corresponding to Milankovitch cycles. Moving-window spectral analyses (windows of 130 kyr stepped by 10 kyr) over the last 320 kyr suggest that these main frequencies are stable over the length of the record.

The variations of main ion concentrations such as MSA, Cl^-, NO_3^-, SO_4^{2-}, Na^+, Mg^{2+} and Ca^{2+}, etc were also recovered from the Dome Fuji ice core. These variations are inversely correlated with temperature. The concentrations of both terrestrial and marine substances are high in glacial periods, and low in interglacial periods. This suggests that meridional transport was strengthened in glacial periods, which compensated for longer transport paths due to greater sea-ice cover. Spectral analyses of chemical variations show cycles similar to the dominant periodicities of temperature.

Acknowledgments

We thank JARE party members and collaborators for their cooperative efforts. This work is a contribution of the Dome Fuji Program, supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

Akaike, H. (1969a): Fitting autoregressive models for prediction. Ann. Inst. Statist. Math., **21**, 243–247.

Akaike, H. (1969b): Power spectrum estimation through autoregressive model fitting. Ann. Inst. Statist.

Math., **21**, 407–419.

Barnola, J.M., Raynaud, D., Karotkevich, Y.S. and Lorius, C. (1987): Vostok ice core provides 160,000-year record of atmospheric CO_2. Nature, **329**, 408–414.

De Angelis, M., Steffensen, J.P., Legrand, M., Clausen, H. and Hammer, C. (1997): Primary aerosol (sea salt and soil dust) deposited in Greenland ice during the last climatic cycle: Comparison with east Antarctic records. J. Geophys. Res., **102** (C12), 26681–26698.

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.

Fujii, Y., Watanabe, O., Furukawa, T., Kamiyama, K., Motoyama, H., Kohno, M., Matoba, S., Igarashi, M., Satow K. and Suzuki, T. (2002): Role of terrestrial dust in climate changes during past 320 k years recorded in Dome Fuji ice core, Antarctica. The 25th Symposium on Polar Meteorology and Glaciology, Program and Abstract, Nov. 20–21, 2002. Tokyo, Natl Inst. Polar Res., 1–2 (in Japanese with English abstract).

Fujita., S., Kameda, T. and Fujii, Y. (1998): Glaciological data collected by the 37th Japanese Antarctic Research Expedition during 1996–1997. JARE Data Rep., **234** (Glaciology 27), 46 p.

Grootes, P.M., Stuiver, M., White, J.W.C., Johsen, S. and Jouzel, J. (1993): Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. Nature, **366**, 552–554.

Hino, M., ed. (1977): Supekutoru Kaiseki (Spectral Analysis). Tokyo, Asakura Shoten, 300 p. (in Japanese).

Iizuka, Y., Fujii, Y., Hirasawa, N., Suzuki, T., Hara, K., Furukawa, T. and Matsuoka, K. (2002): Depletion of surface ion concentration in summer precipitation and snow pack at Dome F, Antarctica. The 25th Symposium on Polar Meteorology and Glaciology, Program and Abstract, Nov. 20–21, 2002. Tokyo, Natl Inst. Polar Res., 9 (in Japanese with English abstract).

Jouzel, J., Lorius, C., Petit, J.R., Genthon, C., Barkov, N.I., Kotlyakov, V.M. and Petrov, V.M. (1987): Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). Nature, **329**, 403–408.

Jouzel, J., Barkov, N.I., Barnola, J.M., Bender, M., Chappelaz, J., Genthon, C., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Petit, J.R., Raynaud, D., Raisbeck, G., Ritz, C., Sowers, T., Stievenard, M., Yiou, F. and Yiou, P. (1993): Extending the Vostok ice-core record of palaeoclimate to the penultimate glacial period. Nature, **364**, 407–412.

Jouzel, J., Waelbroeck, C., Malaize, B., Bender, M., Petit, J.R., Stievenard, M.,.Barkov, N.I., M. Barnola, J., King, T., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Raynaud, D., Ritz, C. and Sowers, T. (1996): Climatic interpretation of the recently extended Vostok ice record. Climate Dyn., **12**, 513–521.

Legrand, M. (1995): Sulphur-derived species in polar ice: a review. Ice Coe Studies of Global Biogeo-chemical Cycles, ed. by R.J. Delmas. Berlin, Sprnger, 91–119. (NATO ASI Series I: Global Environmental Change 30.)

Legrand, M. and Mayewski, P.A. (1997): Glaciochemistry of polar ice cores: a review. Rev. Geophys., **35**, 219–243.

Lorius, C., Jouzel, J., Ritz, C., Merlivat, L., Barkov, N.I., Korotkevich, Y.S. and Kotlyakov, V.M. (1985): A 150,000-year climatic record from Antarctic ice. Nature, **316**, 591–596.

Muller, R.A. and MacDonald, G.J., ed. (2000): Ice Ages and Astronomical Causes: Data, Spectral Analysis and Mechanisms. Chichester, Praxis Publishing/Springer, 318 p.

Parrenin, F., Jouzel, J., Waelbroek, C., Ritz, C. and Barnola, J.M. (2001): Dating the Vostok ice core by an inverse method. J. Geophys. Res., **106**, 31837–31851.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M. *et al*. (1999): Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature, **399**, 429–436.

Watanabe, O., Satow, K., Shoji, H., Motoyama, H., Fujii, Y., Narita, H. and Aoki, S. (2003): Dating of the Dome Fuji, Antarctica deep ice core. Mem. Natl Inst. Polar Res., Spec. Issue, **57**, 25–37.