Korean Journal of Polar Research 8(1, 2): 155-162

Global Climate Change and Deep Ice Core Drilling at Dome Fuji, Antarctica

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ABSTRACT. Deep ice core drilling was carried out to a depth of 2,503.52 m in 1995 and 1996 at Dome Fuji, as a part of a comprehensive glaciological study to clarify present and past glaciological/climatological features of the Antarctic ice sheet in east Queen Maud Land. According to the oxygen stable isotope analysis and simple age calculation, the ice core is thought to cover the past 350 kyears which involves three glacial-interglacial cycles. We show our conceptional model of global climate change during glacial-interglacial cycles and outline our core analyses.

Key Words: Antarctica, climate change, global change, ice core, paleoenvironment

Background of the Project

Japanese Antarctic Research Expeditions (JARE) have collected glaciological, climatological and geochemical data on the ice sheet in east Queen Maud Land since 1968. As a part of the IGBP (International Geosphere-Biosphere Programme) Past Global Changes (PAGES) core project and the International Trans Antarctic-Scientific Expedition (ITASE), the Dome Fuji Project was designed as a comprehensive glaciological study to clarify present and past glaciological/climatological features of the Antarctic ice sheet in east Queen Maud Land.

The project mainly consists of a glaciological traverse study from the ice sheet margin to the top of Dome Fuji and deep ice coring at Dome Fuji Station, and was carried out in 1991-1997.

Field works

Traverse survey

The oversnow traverse party of the JARE conducted glaciological and climatological observations and found the location of the top of the second highest dome in the Antarctica (Ageta *et al.* 1989) in 1985. The project extended the study area from the coast area to Dome Fuji, the summit of Shirase and Ragnhild drainage basins in 1991 and 1992 (Fujii *et al.* 1995; Kamiyama *et al.* 1994; Fig. 1). Glaciological data such as surface elevation, ice thickness, surface ice flow velocity, snow accumulation, snow temperature-depth profiles, stratigraphic and density profiles and snow surface features have been collected along the traverse routes.

Surface and bedrock topographies around Dome Fuji

The surface topography of the dome is very smooth and flat as shown in Fig. 2; surface elevations at six radial points 30 km from the dome summit are only 7 m to 30 m lower than the summit, the mean being 20 m. The mean surface slope in the circle of a radius of 30 km is estimated at about 1/1500.

A topographical map of the bedrock around the Dome Fuji is shown in Fig. 2. It is based on radio-echo sounding data collected in 1992/93 (Maeno *et al.* 1994).

The location of Dome Fuji station was decided on

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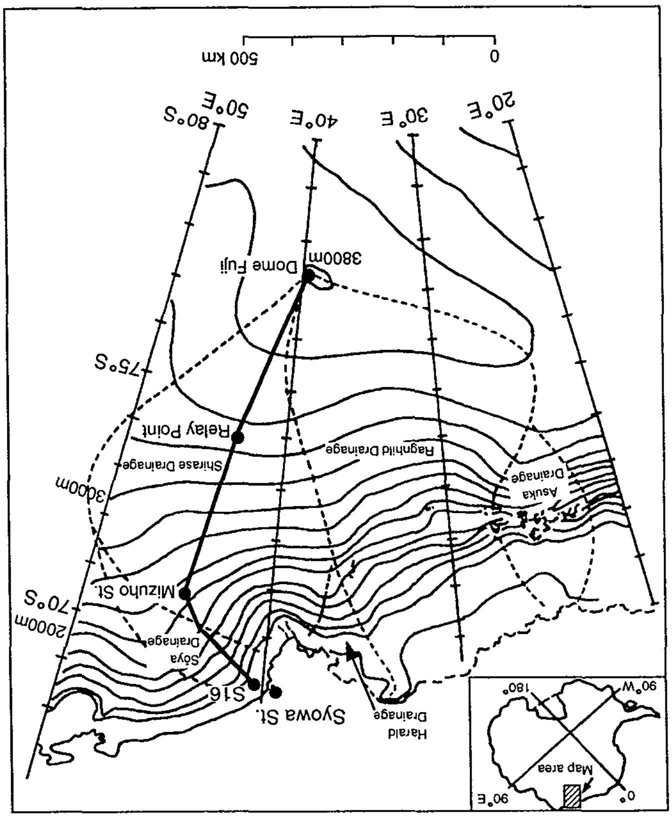

Fig. 1. Research area of the Dome Fuji Project with ice divides of the drainage basins (Nishio and Ageta 1997) and traverse route to Dome Fuji.

the basis of both surface and bedrock topographies. Dome Fuji station is situated above a relatively flat bedrock about 800 m in altitude. The bedrock topography around the dome exhibits what appears to be a saddle point. Bedrock hills higher than 1,000 m a.s.l. are located to the southeast and the northwest, and lowlands lower than 600 m a.s.l. are located to the east and the west.

The ice thickness at the dome summit was measured as 3,060 m by careful radio echo sounding in 1996.

Drilling site

The summit of Dome Fuji is an ideal place for deep ice core drilling because of the place without horizontal ice movement and melting, far remote from anthropogenic activities and with enough thickness of ice. In other words, Dome Fuji core is expected to have less disturbances and noises of paleoclimate records.

Surface traverse observation, snow pit work and 10 m deep drilling provided the following information on Dome Fuji (Ageta *et al.* 1989). Ice thickness was measured by radio echo sounding in 1996.

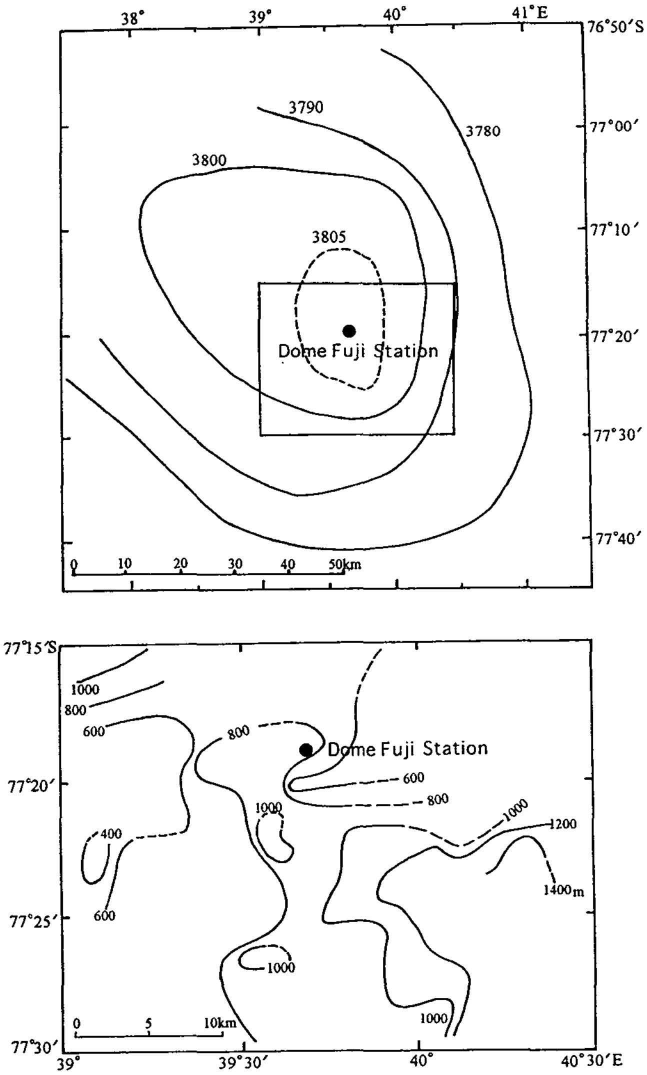

Fig. 2. Surface topography of Dome Fuji (above), showing the area of bed rock topography (below).

- Site location: 77° 19' 01" S, 39° 42' 12" E
- Altitude: 3,810 m a.s.l.
- Ice thickness: 3,060 m estimated from radio echo sounding
- 10 m snow temperature: -58.0°C
- Mean annual net accumulation of snow from 1966 to 1985: 3.2 cm in water equivalent

Deep Ice Core Drilling at Dome Fuji Station

We developed a deep ice core drilling system after field experiments in Antarctica (1988 and 1989), at Dome GRIP, Greenland (1991 and 1992) and at

Rikubetsu, Japan (1992, 1993 and 1994) (Tanaka *et al.* 1994). Pilot borehole drilling and the casing were carried out to a depth of 112 m at Dome Fuji in 1993. Dome Fuji station was constructed in 1994 and deep ice core drilling started in 1995. The drilling reached to a depth of 2,503 m in 1996.

Casing

A pilot borehole with an inside diameter of 135 mm was drilled to 112 m and was reamed to 250 mm in diameter for fiberglass reinforced casing (Johnsen *et al.* 1994) in 1993 (Motoyama *et al.* 1995). The casing was mounted to a depth of 86 m. Prior to the deep ice coring in 1995, the casing was sealed at the bottom by refrozen wet snow to prevent the drill from catching against the bottom end of casing when it was pulled up.

Borehole liquid

The borehole liquid was carefully chosen from the viewpoints of viscosity and density at temperature as low as -60°C effects on ice core quality, drill, human health and environment and no danger of flammability or volatility (Fujita *et al.* 1994). Finally we chose n-butyl acetate (Gosink *et al.* 1994) which has low viscosity and appropriate density in the temperature condition at Dome Fuji.

Drill system

An electromechanical deep ice coring system was developed starting in 1988. Table 1 shows the fundamental specifications. It was designed as a) light, b) easy to operate and c) safe under circumstances at Dome Fuji (Tanaka *et al.* 1994).

The drill is of double tube type consisting of an outer tube and an inner barrel (or a core barrel, 2.3 m long) with three cutters. Spirals are attached to the outer side of the inner barrel to transport chips upward while the barrel is rotating to cut ice. Above the core barrel, chips are forced up into a chip chamber (3.3 m long) by a fin like booster.

The pressure tight chamber that contains the motor, reduction gears and computer section was designed for 3,500 m liquid filled drilling. On the control room computer screen, 25 monitoring parameters are updated every second. The important parameters such as the cable tension, the cutter load and the inclination etc. are shown graphically against depth or time.

Table 1. Specification of a deep ice core drill system used at Dome Fuji

Item	Specification
Drill	outer diameter: 122 mm, length: 8.54 m, weight: 20kg, core diameter: 94 mm, max core length: 2.24 m, hole diameter: 135 mm (nominal), drill motor: 600 W DC brushless
Winch	motor: 11 kW, max load: 3.4 t
Cable	length: 3,500 m, steel armored, 7 conductors, outer diameter: 7.72 mm, breaking strength: 37.4 kN
Tower	length: 10.5 m, steel truss structure, tilt by small winch
Monitoring	Cable length, cable tension, winch speed, power supply voltage, motor voltage, motor current, motor rotation, cutter rotation, cutter load, drill inlination, hole liquid pressure, temperatures (gear section, drill motor, drill computer, hole liquid, winch, drill site), alarm signals (antitorque failer, pressure tight failer)

The winch speed can be delicately controlled by a frequency dial even at slow speed such as 1 cm min^{-1}. For safety and ease of operation, one can set the threshold values of depth and cutter load to stop the winch. Alarm signals are also set to draw the operator's attention.

Because of its low energy consumption, a generator of 28 kW has enough capacity to supply electricity to the total drill system even when the core process line is active.

Drilling operation

Ice core drilling started on August 23, 1995 from the bottom of a pilot borehole at a depth of 112 m. The drilling terminated at a depth of 2,503.52 m on December 8, 1996. Figure 3 shows the drilling operation which was carried out by two drill operators on a two-shift basis. The temperature of the drilling site was kept in the range -25 to -35°C. The total numbers of drilling and chip collection runs were 1370 and 836 respectively. The average length of core obtained per run was 1.75 m.

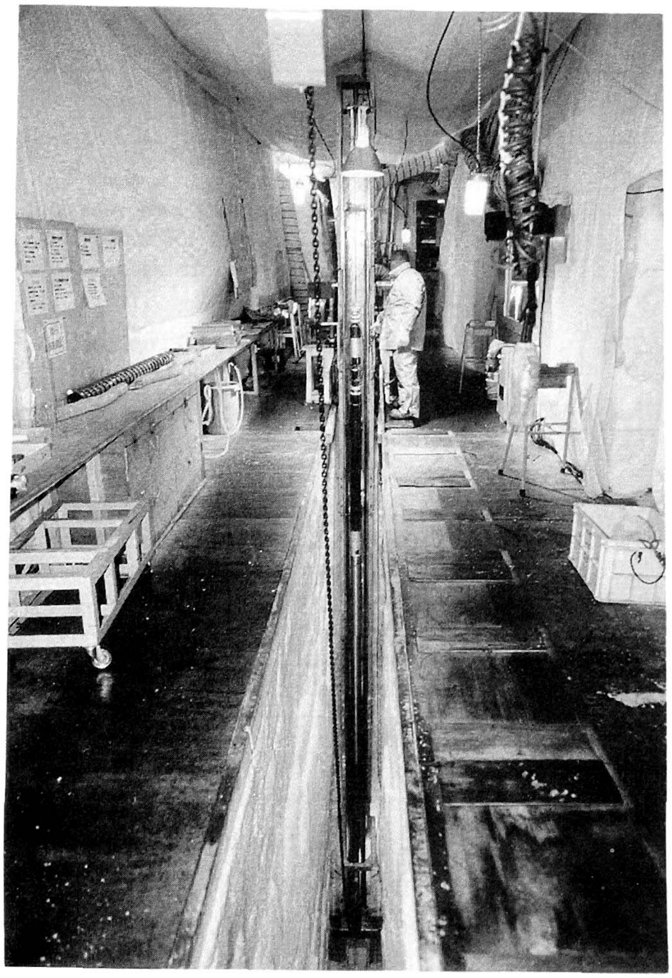

Fig. 3. Deep ice core drilling at Dome Fuji Station. The drilling was carried out by two drillers on a two-shift basis.

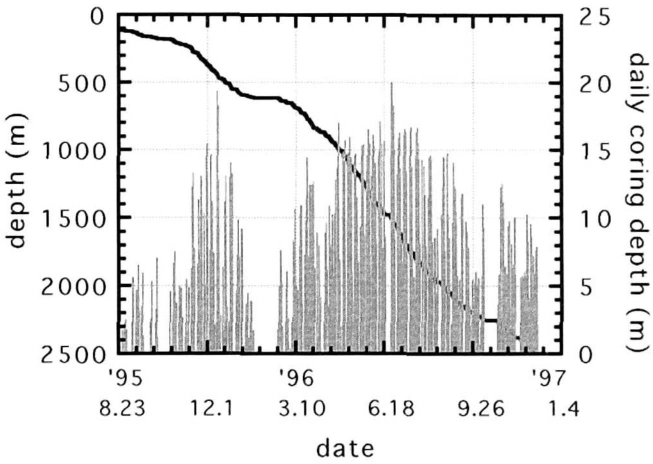

Fig. 4. Drilling progress at Dome Fuji in 1995 and 1996.

Table 2. List of basic analyses of the Dome Fuji deep ice core

Discipline	Item	Method
In-situ	AC-ECM, DC-ECM, stratigraphical observation, density	ECM system
Stable isotope	$\delta^{18}O$, δD, $\delta^{13}C$, $\delta^{15}N$	MS (mass spectrometer)
Major anions	Cl, NO_3, SO_4, CH_3COO, HCOO, MSA, NO_2, C_2O_4	IC (ionchromatograph
Major cations	Na, K, Mg, Ca, NH_4, H (pH)	IC, pH meter
Microparticles	concentration, size distribution, composition	laser particle counter, EPMA, INAA, ICP-MS, etc.
Trace metals	Al, Fe, Zn, Pb, Cu, etc.	ICP-MS
Organic matters	DOC, TOC, DMS, fatty acids, carboxylic acids, bacteris, etc.	GC, GC-MS HTCO, etc.
Trace gases	CO_2, CH_4, CO, O_2	GC, MS
Physical properties	grain size, ice fabrics, total gas contents, air clathrate, cloudly bands, etc.	light-scattering tomography, interferometer, etc.

The quality of the core was fortunately excellent through the whole depths even in the brittle zone from 500 to 840 m in depth due to the small depth of the cut, as small as 0.2 mm because of ice hardness at -50 to -60°C. The borehole was kept almost vertical, deviating not more than 0.5° until 1800 m but increased gradually to 4.6° at 2,250 m in depth. At deeper depths, the inclination decreased.

Liquid temperature increased from -55°C at shallow depths to -20°C at 2,500 m in depth. The ice chip collection rate was improved particularly at depths deeper than 2,000 m because ice could be cut by cutters with larger depth of cut. However we needed at least one day to collect chips in a week. Figure 4 shows the penetration rate and daily coring depth during the drilling in 1995 and 1996.

Core Analyses

In-situ analyses

In-situ core analyses consisting of electrical conductivity measurements (ECM), stratigraphical observation and bulk density measurements were carried out. ECM includes both DC measurements (Hammer 1980) and AC (Sugiyama *et al.* 1995). Stratigraphical observations include careful exami-

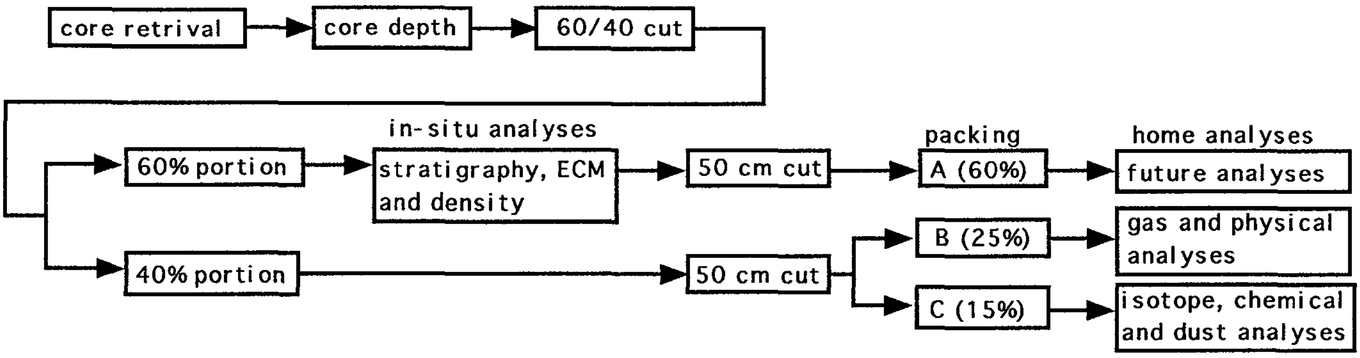

Fig. 5. *In-situ* core processing procedure at Dome Fuji.

nation of tephra layers, cloudy bands and air bubble/clathrate hydrate.

After ice core retrieval, the cores were first stored in a storage trench for 1 to 4 months. Then they were processed. Figure 5 shows a core processing procedure carried out at Dome Fuji.

In the processing line, first logging and bulk density measurements were made. Then cores were cut by 60% and 40% along the core axis. The cutting surface of the former parts (60%) are used for both AC- and DC-ECMs and stratigraphical observation. At the end of the core process line, cores were finally cut into three pieces along the core axis: 60% (A core); 25% (B core) and 15% (C core); and cut at every 50 cm for packing. Room temperature was normally kept at around -20°C for the stable ECM. Up to January 1997, the processing were carried out down to the depth of 2,251 m. The cores below this depth were processed by June 1997.

25 tephra layers were observed in the core down to 2,251 m. Among them two were found in between 500 m and 600 m. The other 23 were found below 1,000 m down to 2,251 m. The thickness is in the range from 1 to 22 mm.

The cores were brittle at depths between around 500 m and around 840 m. The starting depth of the brittle zone is roughly the same as the depth at which the first cloudy bands and clathrate hydrate crystals appeared. More than 700 distinct cloudy bands were found as well as many indistinct ambiguous layers. Most of them were found in three depth ranges, around 550 m, 1,000 m and 2,000 m. In contrast, in the other depth ranges they were rare. Visible air bubbles have not been observed at depths below about 1,100 m.

Home analyses

The core analyses started for top 430 m in 1996 and for the core below 430 m in 1997 at the National Institute of Polar Research and at some University Institutes and Faculties as a cooperative research works of the project.

The items of basic analyses are listed in Table 2. The analyses involve several primary disciplines; 1) stable oxygen and hydrogen isotope ratios for reconstruction of the paleoclimate change, 2) major anion and cation concentrations for study of paleogeochemical cycle and paleoenvironment changes, 3) microparticles and trace metals for study of change of terrestrial dust source and the transportation processes as well as volcanic events, 4) trace gases for study of greenhouse effect on climate change involving the valuation of biological process, 5) organic compounds for study of biological production and the relation to climate change through such processes as CO_2 biological pump and cloud condensation nuclei of MSA, and 6) physical properties for study of air hydrate, cloudy bands, grain size, total air content and so on. These physical properties are thought to reflect climatic condition during densification of snow to ice.

Conception of Global Climate Change

Global circulation of substances and gases as core signals

The Antarctic ice sheet preserves signals of global

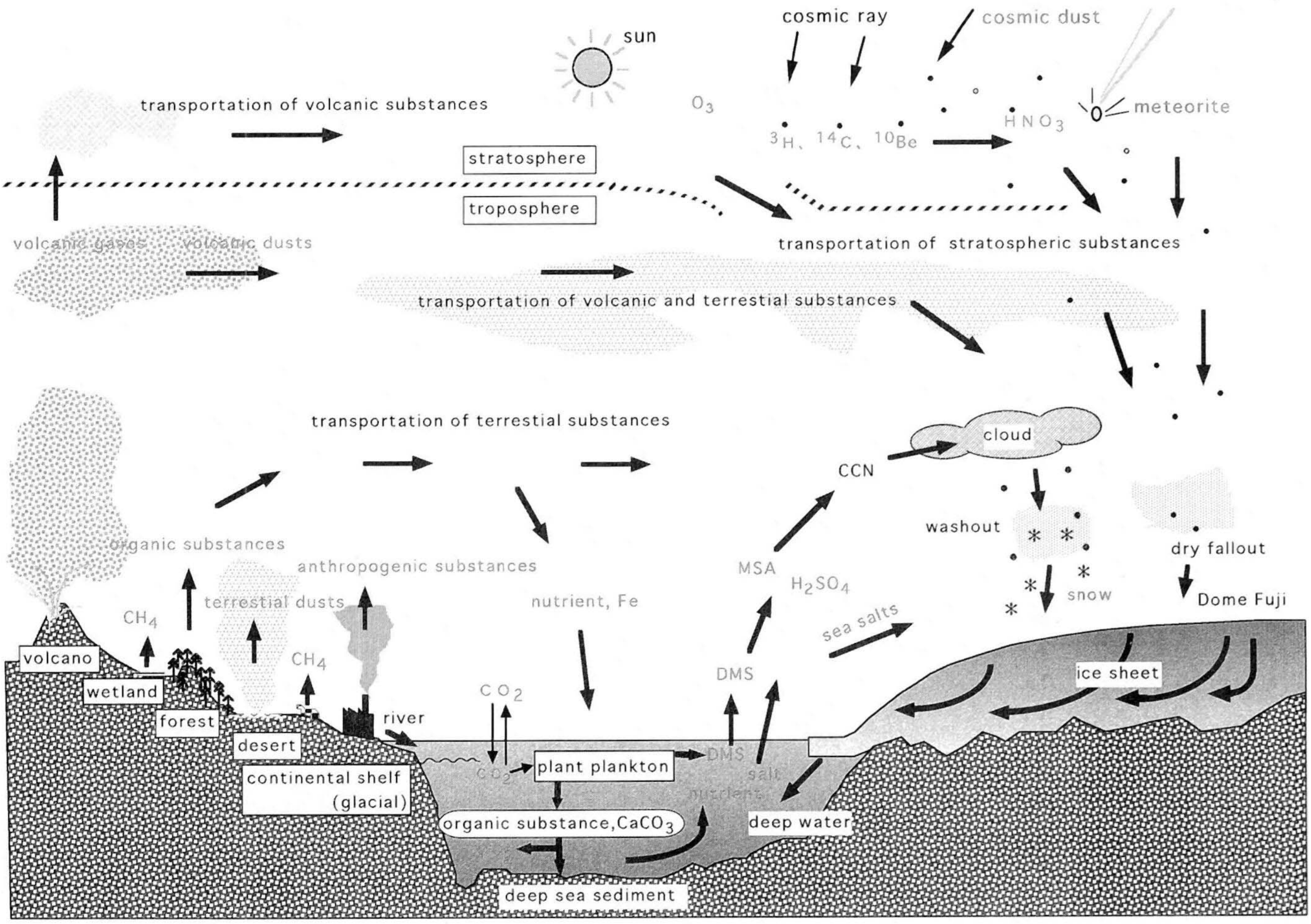

Fig. 6. Circulation of substances and gases from various sources and their transportation to the Antarctic ice sheet.

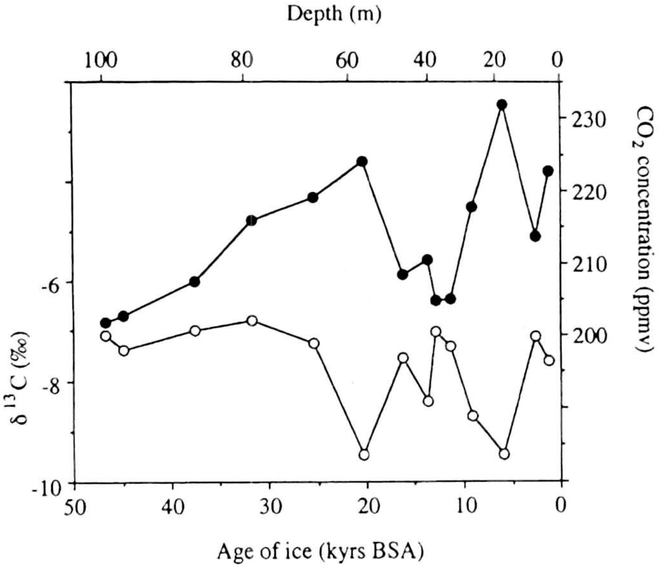

Fig. 7. Comparison of the CO_2 concentration (solid circles) with its $\delta^{13}C$ values (open circles) for the South Yamato core. Measured values of both components are plotted against the age of ice relative to surface ice. (Machida *et al.* 1996).

paleoenvironment change during the last some hundred thousand years. Figure 6 shows the conceptional schema of the emission of substances and gases from various sources and the transportation to the Antarctic ice sheet through lower and upper troposphere and stratosphere.

Large scale volcanic eruption emits both great amount of gases and dusts to stratosphere. The volcanic substances are globally spread and transported to polar regions. For example, signal of Tambora eruption in 1815 is detected in both Greenland and the Antarctic ice cores (Dai *et al.* 1991). These volcanic signals as well as tephra layers are the good time markers for core dating (ex. Johnsen *et al.* 1992). The 25 tephra layers observed in Dome Fuji core will provide new timescale for past 350 kyears.

Dusts from arid regions and exposed continental shelf are the most probable sources of microparticles in ice core during the Holocene (or the interglacial)

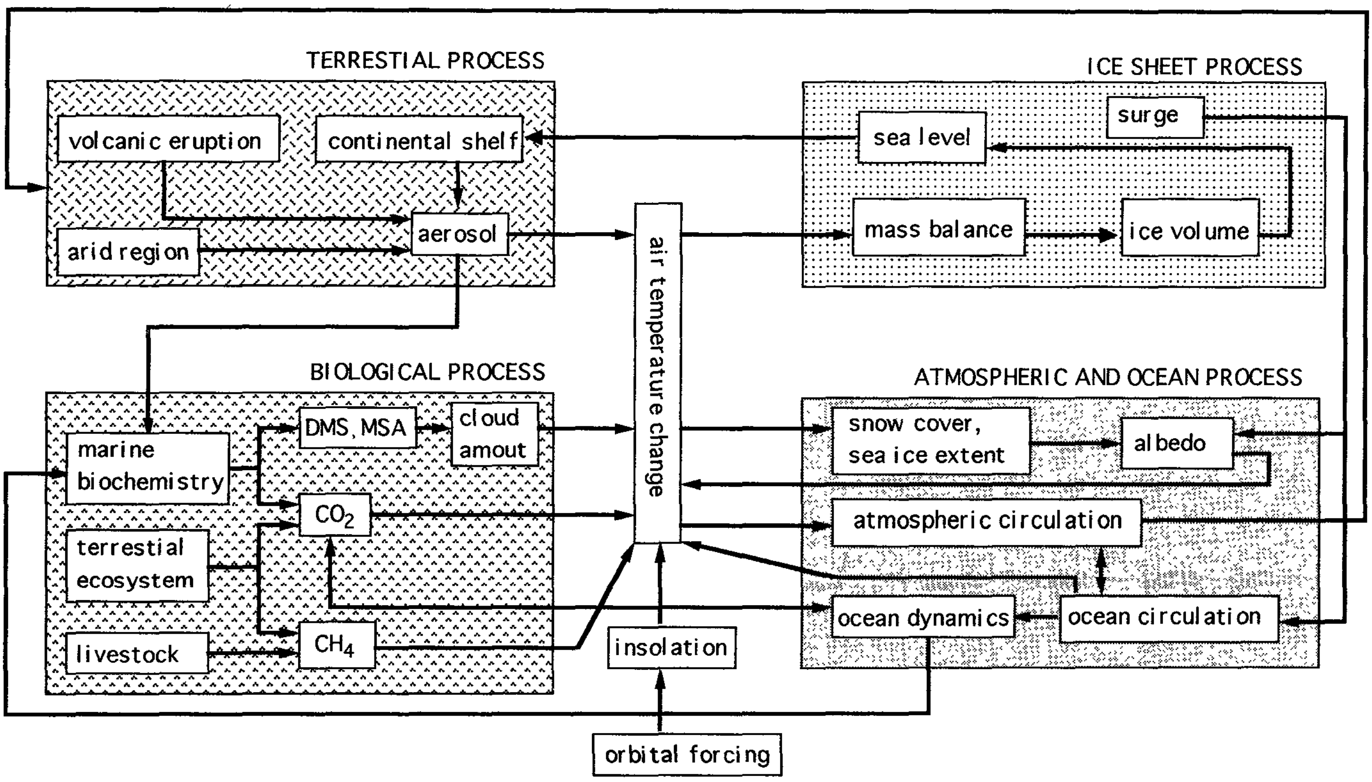

Fig. 8. Mechanism of the global climate change in glacial-interglacial cycles.

and the glacial (Grousset *et al.* 1992), respectively.

Oceanogenic substances such as sea salts are transported to the polar ice sheets through lower troposphere by low pressure disturbance. The concentration decreases with distance from the coast.

Transportation of trace gases and gas derived aerosols differs much from that of particulate matters; that is, they are spread to upper troposphere and to stratosphere and are transported to polar ice sheets. Subsidence of upper tropospheric and stratospheric air mass is important process in the inland plateau of the Antarctic ice sheet for gas derived aerosols and some stratospheric substances such as nitrate and tritium (Kamiyama *et al.* 1989).

Global climate change in glacial-interglacial cycles

The global climate change related to glacial-interglacial cycles has been understood with data from deep sea and ice sheet cores.

The CLIMAP (Climate, Long-range Investigation, Mapping and Prediction; established in 1970) project revealed that the Indian Ocean deep cores included dominant periodicities almost close to those predicted by Milankovitch (Hay *et al.* 1976). While perturbations in the Earth's orbit are responsible for glacial cycle, climate modeling experiments cannot explain cooling during the glacial without reference to feedback effects of such as greenhouse gases and aerosol concentration (Manabe and Broccoli 1985).

Vostok ice core data show that the atmospheric concentration of greenhouse gases oscillated in close harmony with global temperature changes during past some hundred thousand years, indicating two are certainly related and greenhouse effect amplifies the Milankovitch signal (Lorius *et al.* 1990). Furthermore, biological processes seem to be very important for atmospheric CO_2 concentration as shown in Fig. 7 (Machida *et al.* 1996).

Ice core recovered by the GRIP (Greenland Icecore Project; 1990-1992) reveals 22 interstadial (warm) events during the last glacial with very rapid warming and moderate cooling (Johnsen *et al.* 1992). Bond *et al.* (1993) have shown that records of sea surface temperature from North Atlantic sediments spanning the past 90 kyears closely matched those in the GRIP ice cores and that an enormous discharge of icebergs into the North Atlantic (Heinrich event) correlated with the interstadial cycle, suggesting the important role of the North Atlantic Deep Water (NADW) formation in the abrupt warming. The interstadials lasted longer than 2,000 years are recorded in the Vostok ice core (Bender *et al.* 1994).

The correlations between climate records from North Atlantic sediments and Greenland ice suggest that interrelation between atmosphere and ocean plays an important role in global climate change.

As we have briefly given an overview of the recent scientific results on global climate change, the mechanism is not fully understood yet. However, orbital forcing, greenhouse effect, albedo, aerosols and NADW (interrelation between atmosphere and ocean) are the key words for understanding mechanism of global climate change.

We have hitherto described recent scientific results on mechanism of global climate change and we propose the probable scenario in Fig. 8.

References

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

Bender M., Sowers T., Dickson M-L., Orchardo J., Grootes P., Mayewski P.A., and Meese D.A. 1994. Climate correlations between Greenland and Antarctica during the past 100,000 years. *Nature* **372:** 663-666.

Bond G., Broecker W., Johnsen S., McManus J., Labeyrie L., Jouzel J., and Bonani G. 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature* **365:** 143-147.

Dai J., Mosley-Thompson E., and Thompson L.G. 1991. Ice core evidence for an explosive tropical volcanic eruption 6 years preceding Tambora. *J. Geophys. Res.* **96**: D9, 17361-17366.

Fujii Y., Motoyama H., and Azuma N. 1995. Glaciological data collected by the 30th, 31st and 32nd Japanese Antarctic Research Expeditions in 1989-1991. *JARE Data Reports (Glaciology)* **201**: 89 pp.

Fujita S., Yamada T., Naruse R., Mae S., Azuma N., and Fujii Y. 1994. Drilling fluid for Dome F project in Antarctica. *Mem. National Inst. Polar Res., Spec. Iss.* **49:** 347-357.

Gosink T.A., Kelly J.J., Tumeo M.A., Koci B., Stanford K., Zagorodnov V., and Ehlert G. 1994. Fluids for use in deep ice-core drilling. *Mem. National Inst. Polar Res., Spec. Iss.* **49**: 335-346.

Grousset F.E., Biscaye P.E., Revel M., Petit J-R., Pye K., Joussaume S., and Jouzel J. 1992. Antarctic (Dome C) ice-core dust at 18 k.y.: Isotopic constraints on origins. *Earth Planet. Sci. Lett.* **111:** 175-182.

Hay J.D., Imbrie J., and Shackleton N.J. 1976. Variations in the earth's orbit: Pacemaker of the ice ages. *Science* **235:** 1156-1167.

Johnsen S.J., Gundestrup N.S., Hansen S.B., Schwander J., and Rufli H. 1994. The new improved version of the ISTUK ice core drill. *Mem. National Inst. Polar Res., Spec. Iss.* **49:** 9-23.

Johnsen S.J., Clausen H.B., Dansgaard W., Fuhrer K., Gundestrup N., Hammer C.U., Inversen P., Jouzel J., Stauffer B., and Steffensen J.P. 1992. Irregular glacial interstadials recorded in a new Greenland ice core. *Nature* **359:** 311-313.

Kamiyama K., Ageta Y., and Fujii Y. 1989. Atmospheric and depositional environments traced from unique chemical compositions of the snow over an inland high plateau, Antarctica. *J. Geophys. Res.* **94:** D15, 18, 515-519.

Kamiyama K., Furukawa T., Maeno H., Kishi T., and Kanao M. 1994. Glaciological data collected by the 33rd Japanese Antarctic Research Expedition in 1992. *JARE Data Reports (Glaciology)* **194:** 67 pp.

Lorius C., Jouzel J., Raynaud D., Hansen J., and Le Treut H. 1990. The ice-core record: Climate sensitivity and future greenhouse warming. *Nature* **347:** 139-145.

Machida T., Nakazawa T., Narita H., Fujii Y., Aoki S., and Watanabe O. 1996. Variations of the CO_2, CH_4, and N_2O concentrations and $\delta^{13}C$ of CO_2 in the glacial period deduced from an Antarctic ice core, south Yamato. *Proceed. NIPR Symp. Polar Meteorol. Glaciol.* **10:** 55-65.

Maeno H., Kamiyama K., Furukawa T., Watanabe O., Naruse R., Okamoto K., Suitz T., and Uratsuka S. 1994. Using a mobile radio echo sounder to measure bedrock topography in east Queen Maud Land, Antarctica. *Proceed. NIPR Symp. Polar Meteorol. Glaciol.* **8:** 149-160

Manabe S. and Broccoli A.J. 1985. The influence of continental ice sheets on the climate of an ice age. *J. Geophys. Res.* **90:** 2167-2190.

Martin J.H. 1990. Glacial-interglacial CO_2 changes: The iron hypothesis. *Palaeoceanography* **5:** 1-13.

Motoyama H., Enomoto H., Furukawa T., Kamiyama K., Shoji H., Shiraiwa T., Watanabe K., Namasu K., and Ikeda H. 1995. Preliminary study of ice flow observations along traverse routes from coast to Dome Fuji, East Antarctica by differential GPS method. *Nankyoku Shiryo (Antarct. Rec.)* **39:** 94-98.

Nishio F. and Ageta Y. 1997. *Ice Sheet Surface. Antarctica: East Queen Maud Land-Enderby Land Glaciological Folio.* National Institute of Polar Research, Tokyo.

Sugiyama K., Fujita S., Sueoka S., Mae S., and Hondoh T. 1995. Preliminary measurement of High-Frequency electrical conductivity of Antarctic ice with AC-ECM technique. *Proceed. NIPR Symp. Polar Meteorol. Glaciol.* **9:** 12-22.

Tanaka Y., Takahashi A., Fujii Y., Narita H., Shinbori K., Azuma N., and Watanabe O. 1994. Development of a JARE deep ice core drill system. *Mem. National Inst. Polar Res., Spec. Iss.* **49:** 113-123.

Received 25 September 1997
Accepted 7 November 1997