Proc. NIPR Symp. Polar Meteorol. Glaciol., **5**, 120–127, 1992

DISTRIBUTION OF MEAN $\delta^{18}O$ VALUES OF SURFACE SNOW LAYERS AND THEIR DEPENDENCE ON AIR TEMPERATURE IN ENDERBY LAND–EAST QUEEN MAUD LAND, ANTARCTICA

Kazuhide SATOW[1] and Okitsugu WATANABE[2]

[1] *Nagaoka National College of Technology, Nishi-katakai-machi, Nagaoka 940*
[2] *National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: Oxygen isotope analyses of surface snow layers have been carried out in Enderby Land–East Queen Maud Land, East Antarctica. The $\delta^{18}O$ values decrease with various parameters including elevation (E: m), distance from the coast (L: km): [$\delta^{18}O(‰) = -0.0069E - 0.0126L - 18.5$], and in particular with mean annual surface temperatures (T: °C), according to a good linear relationship [$\delta^{18}O(‰) = 0.834T - 8.7$] in the temperature range from −20 to −55°C. The relationship with temperature is similar to that derived from a simple model in which an air mass is progressively cooled under Rayleigh conditions as it moves toward the inland plateau. This also suggests that $\delta^{18}O$ values are very closely related to condensation temperature at the top of the inversion layer where snowfall precipitation is formed.

1. Introduction

The relationship between isotopic δ values for oxygen and deuterium and temperature in precipitation has been studied by various authors such as EPSTEIN and MAYEDA (1953), SCHOLANDER *et al.* (1962) and DANSGAARD (1964). Ice core drilling has been carried out in many regions of the world, including the Greenland and Antarctica ice sheets. Isotopic records from the cores make it possible to estimate the climatic change at a given place. But the interpretation of isotopic variation is not so simple, because the δ-value is related to condensation and evaporation processes at various steps in the phase change of water. A broad understanding of the main features of the relationship between $\delta^{18}O$ values in natural water or snow and air temperature at high latitudes has been achieved using the assumption that condensation processes which take place during the cooling of a moist air mass proceed under Rayleigh conditions, where condensation occurs at equilibrium and the condensate is removed from the system immediately after formation (DANSGAARD, 1964).

In the Antarctic ice sheet, a typical seasonal variation of $\delta^{18}O$ values of surface snow layers can be seen in a snowy area like the coastal region with high net accumulation, but cannot always be clearly confirmed on the slope where strong katabatic winds occur, or the inland area where net accumulation is very low (SATOW and WATANABE, 1985, 1990; WATANABE *et al.*, 1988).

10 m firn cores or 2 m pit-snow samples on Enderby Land–East Queen Maud Land, East Antarctica, were collected by the Japanese Antarctic Research Expeditions. From the oxygen isotope analyses of these samples, the characteristics of $\delta^{18}O$ distribution and its dependence on air temperature will be discussed in the area from the coast (69°S) near Syowa Station to the inland: Dome Camp (77°S), Enderby Land–East Queen Maud Land. Though these firn samples were not obtained at the same times, year-to-year variations of $\delta^{18}O$ are not taken into consideration in this paper. The

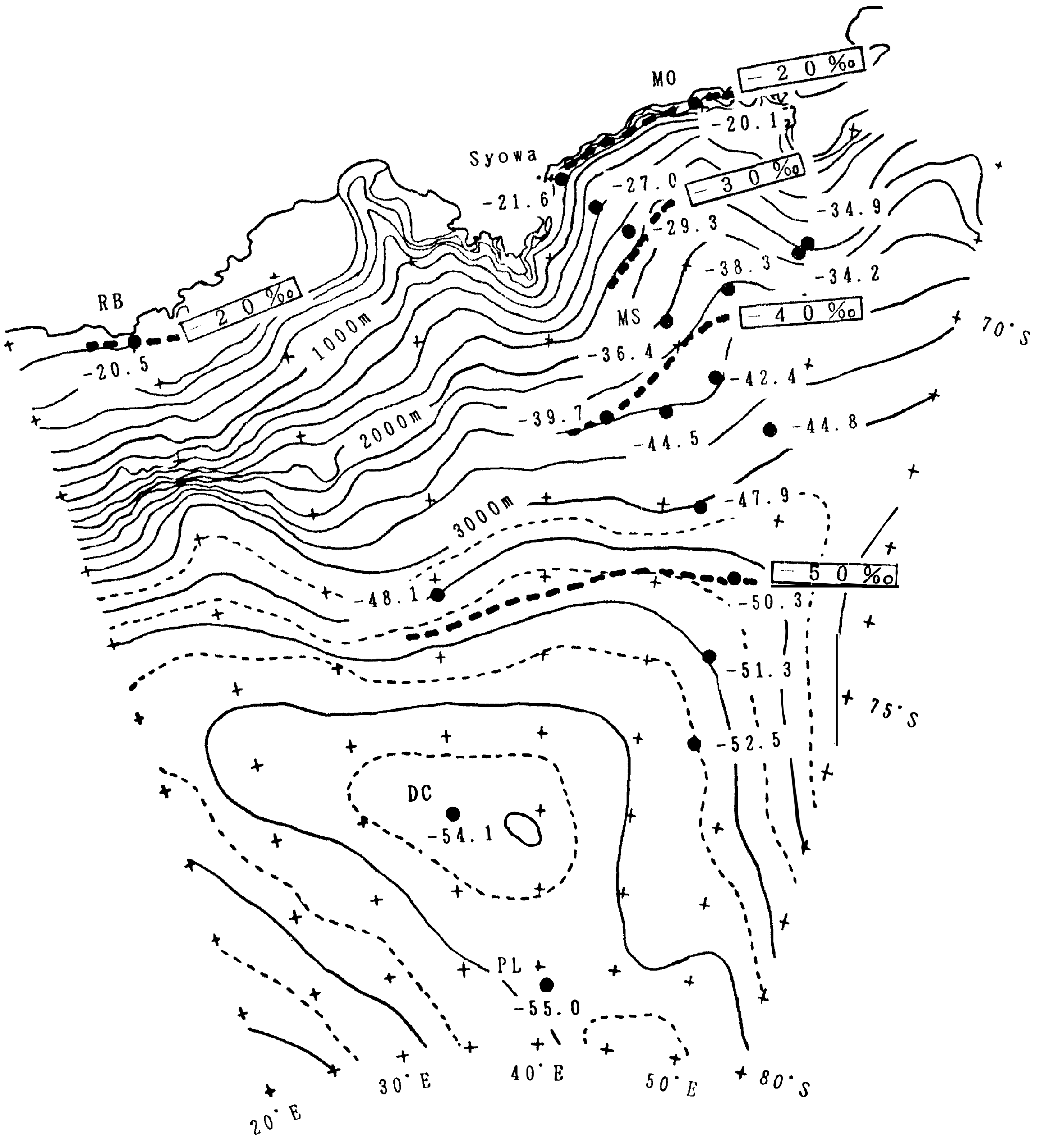

Fig. 1. Isotopic $\delta^{18}O$ values measured in near-surface snow layers of Enderby Land–East Queen Maud Land, Antarctica. Black circles are sample sites; figures are mean $\delta^{18}O$ values (unit: ‰). RB: Roi Baudouin Station, MO: Molodezhnaya Station, MS: Mizuho Station, DC: Dome Camp and PL: Plateau Station.

$\delta^{18}O$ values here should be regarded as the simple average of oxgen-isotope ratios for several years or tens years in 2 m or 10 m snow depth.

2. Regional Distribution of Mean Near-Surface $\delta^{18}O$ Values

A collection of mean $\delta^{18}O$ value measurements of surface snow layers over Enderby Land–East Queen Maud Land are shown in Fig. 1, with $\delta^{18}O$-isolines from $-20‰$ to $-50‰$. Mean surface values from snow samples covering several years or ten years in coastal areas are typically of the order of $-20‰$; they decrease inland, with the lowest value being $-55‰$ at Plateau Station. From this figure, it can be seen that the pattern of $\delta^{18}O$ distribution is similar to that of the elevation contours.

3. Mean Near-Surface $\delta^{18}O$ Values against Elevation

The relation between $\delta^{18}O$ and elevation is shown in Fig. 2. The following good linear relation, which equation is calculated except for three data at the coast, can be seen in Fig. 2;

$$\delta^{18}O(‰) = -0.011E - 11.4\ , \tag{1}$$

where E is elevation (m). This relation shows the difference of 11‰ per 1000 m elevation. The correlation coefficient is 0.99, and its standard deviation is 1.55‰.

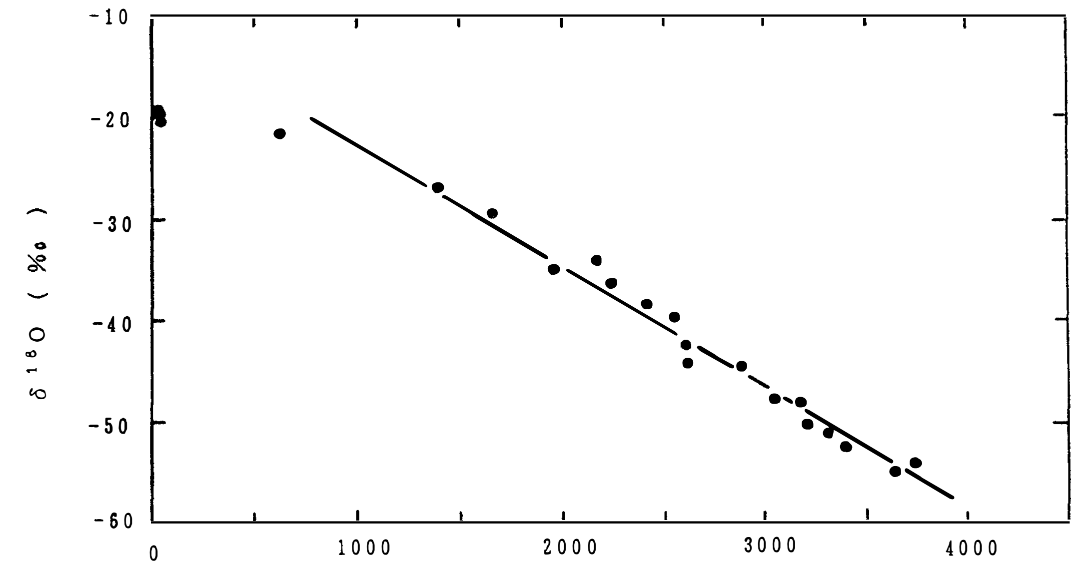

Fig. 2. Mean near-surface $\delta^{18}O$ values of snow plotted against elevation.

4. Mean Near-Surface $\delta^{18}O$ Values against Distance from the Coast

Figure 3 shows the relation between $\delta^{18}O$ values and the distance between a sampling site and the nearest coast. WATANABE *et al.* (1988) gave the following relation:

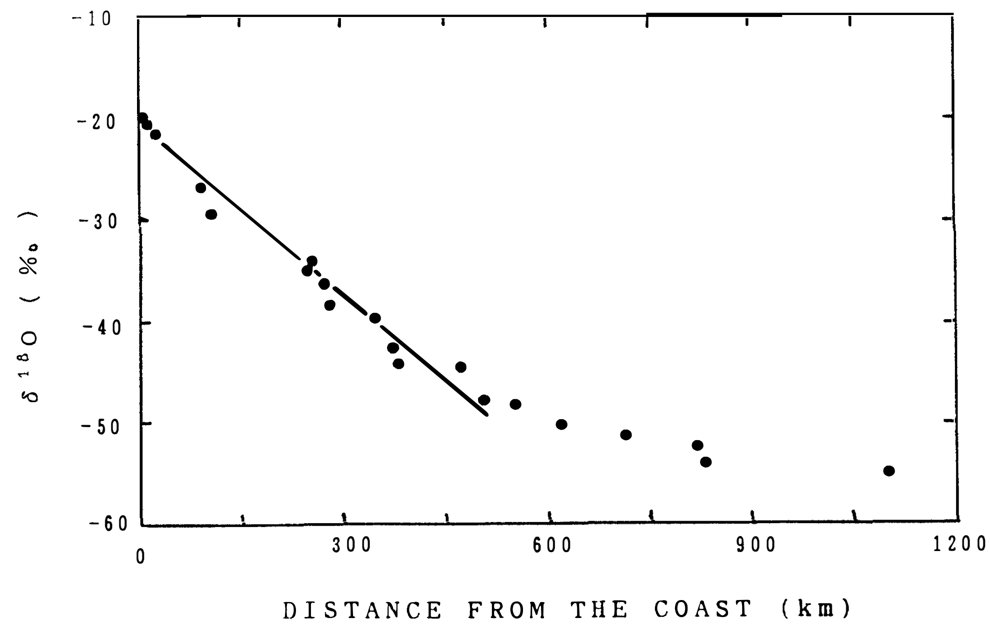

Fig. 3. Mean near-surface $\delta^{18}O$ values of snow plotted against distance from the coast.

$$\delta^{18}O(‰)=7.52L^{0.29} , \tag{2}$$

where L is the distance from the coast (km). In Fig. 3, the linear relation is seen from the coast to 450 km inland, with a lapse rate of 1‰ per 18 km. KOERNER (1979) obtained a decrease of $\delta^{18}O$ values of around 1‰ per 50 km in the Canadian Arctic Islands. On the Antarctic Peninsula, the mean decrease of $\delta^{18}O$ values with distance appears to be around 1‰ per 65 km (SCHWERDTFEGER, 1975). Among these three lapse rates, the value along the Antarctic Peninsula is slightly less than that over the rougher Canadian Arctic Islands, and the lapse rate over the present region on the ice sheet-covered continent is largest. It appears that the mean $\delta^{18}O$ values decrease with distance from the source of moisture as a result of isobaric precipitation processes over level ice shelves, in contrast to the dominance of orographic processes over rising ice sheets as in this region.

By using a linear multiple regression model, the following expression for this region can be obtained as functions of elevation (E: m) and distance from the coast (L: km):

$$\delta^{18}O(‰)=-0.0069E-0.0126L-18.5 , \tag{3}$$

where the multiple correlation coefficient is 0.99. By the use of these partial regression coefficients, it can be derived that the lapse rate of $\delta^{18}O$ values is 1‰ per 145 m in elevation and 1‰ per 79 km distance from the coast, respectively. Farther inland than 400 km in Fig. 3, the elevation effect for the $\delta^{18}O$ value is much smaller than in the coastal region.

5. Discussion of the Relation between Mean Near-Surface $\delta^{18}O$ Values and Mean Surface Temperature

It is widely understood that the 10 m snow temperature in the dry snow zone is roughly equal to the mean annual near-surface air temperature at a given place (SATOW, 1978). Figure 4 shows the good relationship between $\delta^{18}O$ values of snow and 10 m snow temperatures at core sampling sites:

$$\delta^{18}O(‰)=0.834T-8.7\ , \tag{4}$$

where T is 10 m snow temperature (°C). The correlation coefficient is 0.99 and its standard deviation is 1.3‰.

A strong surface air temperature inversion, usually 300–1000 m thick above the surface, develops principally in response to the almost continuous net radiative heat loss from the surface of the Antarctic high plateau throughout the year (for example: PHILLPOT and ZILLMAN, 1970). Figure 5 shows the strength of the temperature inversion plotted against mean near-surface temperature. The lower in mean annual surface temperature (T: °C), the bigger in temperature inversion strength (ΔT: °C). The relation is as follows:

$$\Delta T=-0.364T-4.0\ . \tag{5}$$

It should not be assumed that the mean air temperature above the inversion is the same thoroughly as the mean cloud temperature at which snow is formed. How-

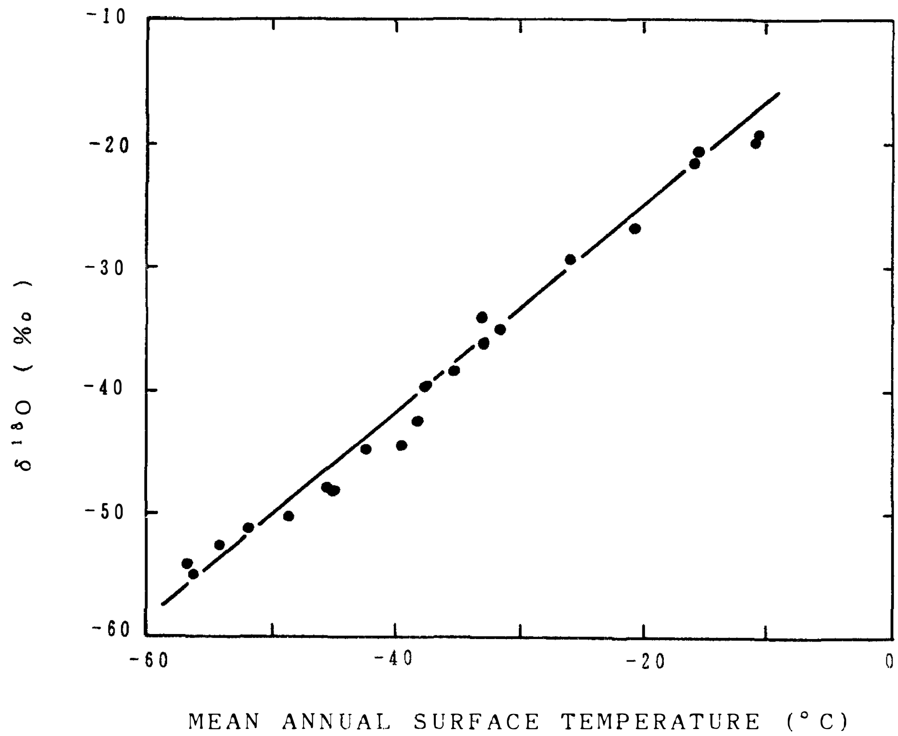

Fig. 4. Mean near-surface $\delta^{18}O$ values of snow plotted against mean annual air temperature at surface level (10 m snow temperature).

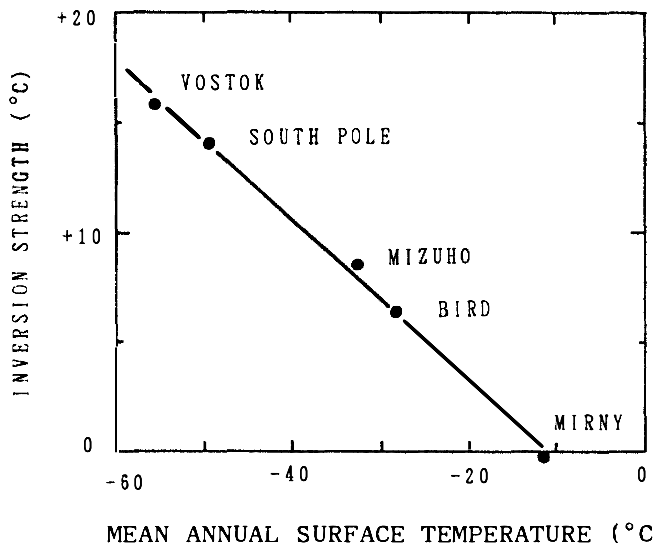

Fig. 5. Relationship between mean annual surface temperature and mean strength of the air temperature inversion above the surface over the Antarctic Continent. The datum at Mizuho Station is after KAWAGUCHI *et al. (1982); and the others are after* ROBIN *(1983).*

ever, the difference is not large at the South Pole, where the mean temperatures above the inversion are within 4°C of the effective precipitation temperature formation (ALDAZ and DEUTSCH, 1967). JOUZEL *et al.* (1983) examined the relationship between isotopic composition ratios of precipitation and the temperatures between the ground and 500 mbar levels at the South Pole. This level was chosen as the upper boundary of the precipitating layer because the contribution of the remainder of the troposphere should be negligible owing to its low moisture content. These investigators concluded that the best correlation is obtained when the maximum tropospheric temperatures are used, tending to justify that precipitation is formed just above the inversion (ROBIN, 1977). So, the mean condensation temperature in the clouds, where the precipitation is formed, is nearer to the temperature at the upper limit of the inversion layer than to the surface temperature. Combining eqs, (4) and (5), we obtain eq. (6),

$$\delta^{18}O(‰)=1.31T_c-3.47\ , \tag{6}$$

where $T_c=T+\Delta T$: condensation temperature (°C) at the top of the inversion layer.

In Fig. 6, line A shows eq. (4), and line A′ shows eq. (6). For comparison, the relation between $\delta^{18}O$ values and 10 m snow temperatures is represented by line B according to data reported by LORIUS and MERLIVAT (1977) for another part of East Antarctica. The $\delta^{18}O$–temperature gradient of 0.834‰/°C (line A) is somewhat larger than that of line B. In addition, the relation at the South Pole (line C), from ALDAZ and DEUTSCH (1967), is plotted through $\delta^{18}O$ values of falling snow in relation to the cloud temperatures at which the snow was formed. Curve D, after ALDAZ and DEUTSCH (1967), is explained as follows. An example of simple model of the isotopic fractionation of water will be here given, that was developed by DANSGAARD (1964). Curve D links results at Roi Baudouin (lat. 70°26′S, long. 24°17′E) with those at the South Pole by assuming that air from Roi Baudouin undergoes moist adiabatic ex-

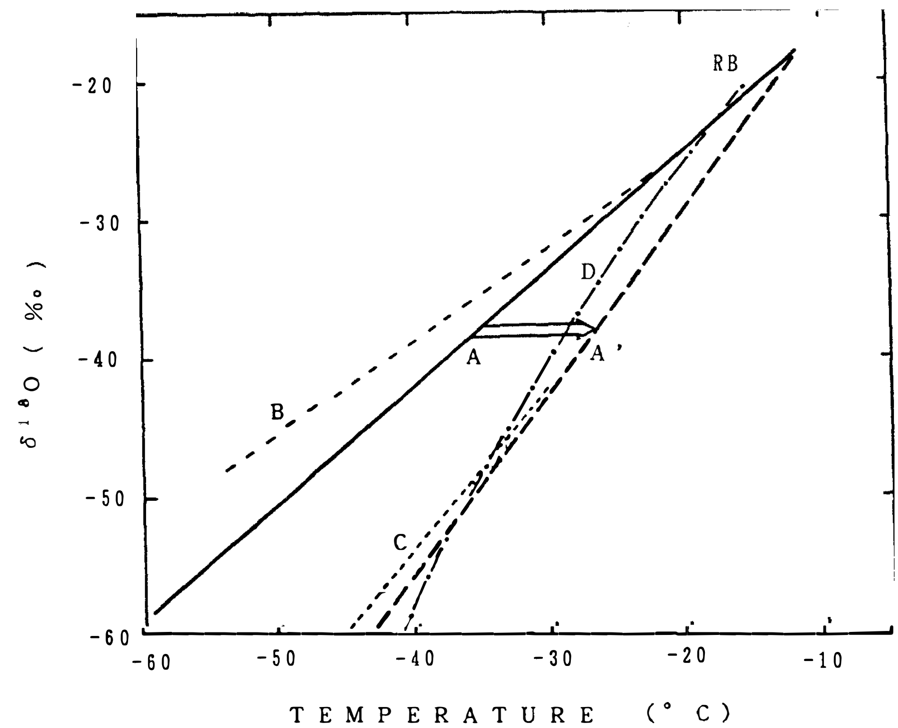

Fig. 6. Isotopic $\delta^{18}O$–temperature relationships. Line A is obtained by eq. (4). Line A′, by eq. (6) calculated from eqs. (4) and (5), shows the relation between $\delta^{18}O$ and air temperature just above the inversion layer. Line B is for the surface layers of firn of East Antarctica (LORIUS and MERLIVAT, 1977). Line C is for clouds at the South Pole from ALDAZ and DEUTSCH (1967). Curve D is calculated for Rayleigh condensation processes with adiabatic cooling from Roi Baudouin Station (RB) toward the inland plateau (ALDAZ and DEUTSCH, 1967).

pansion under Rayleigh condensation processes as it travels up over the Antarctic ice sheet until it reaches the South Pole (ALDAZ and DEUTSCH, 1967). Our obtained line A′ is near line C and curve D. Therefore it can be said that mean $\delta^{18}O$ values of surface snow layers in the present region are very closely related to the mean temperature at the top of the inversion layer at a given places.

6. Conclusion

The $\delta^{18}O$ distribution of surface snow layers was obtained in Enderby Land–East Queen Maud Land, Antarctica, giving the relationships between $\delta^{18}O$ values and elevations, distances from the coast and mean annual surface temperatures (10 m snow temperatures).

Though snow sampling sites for $\delta^{18}O$ analyses have different accumulations, which are high in the coastal area, irregular on the slope with strong katabatic wind and low in the inland area, there is a good linear relationship between mean $\delta^{18}O$ values of surface snow layers and mean annual surface temperatures. It is also suggested that the $\delta^{18}O$ values are closely related to condensation temperature above the inversion layer where snowfall precipitation is formed.

References

ALDAZ, L. and DEUTSCH, S. (1967): On a relationship between air temperature and oxygen isotope ratios of snow and firn in the South Pole region. Earth Planet. Sci. Lett., **3**, 267–273.

DANSGAARD, W. (1964): Stable isotopes in precipitation. Tellus, **16**, 436–468.

EPSTEIN, S. and MAYEDA, T. (1953): Variation of ^{18}O content of waters from natural sources. Geochim. Cosmochim. Acta, **4**, 213–224.

JOUZEL, J., MERLIVAT, L., PETT, J. R. and LORIUS, C. (1983): Climatic information over the last century deduced from a detailed isotopic record in the South Pole snow. J. Geophys. Res., **88**, 2693–2703.

KAWAGUCHI, S., KOBAYASHI, S. and ISHIKAWA, N. (1982): Aerological soundings of the surface boundary layer at Mizuho Station, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **24**, 77–86.

KOERNER, R. M. (1979): Accumulation, ablation, and oxygen isotope variations on the Queen Elizabeth Islands Ice Caps, Canada. J. Glaciol., **22**, 25–41.

LORIUS, C. and MERLIVAT, L. (1977): Distribution of mean surface stable isotopes in East Antarctica: Observed changes with depth in the coastal area. Isotopes and Impurities in Snow and Ice Symposium; Proceedings of the Grenoble Symposium, August/September 1975. Dorking, IAHS, 127–137 (IAHS Publ. No. 118).

PHILLPOT, H. R. and ZILLMAN, J. W. (1970): The surface temperature inversion over the Antarctic Continent. J. Geophys. Res., **75**, 4161–4169.

ROBIN, G. DE Q. (1977): Ice cores and climatic changes. Philos. Trans. R. Soc. London, Ser. B, **280**, 143–168.

ROBIN, G. DE Q., ed. (1983): Ice sheets: Isotopes and temperatures. The Climatic Record in Polar Ice Sheets, Cambridge, Cambridge Univ. Press, 1–18.

SATOW, K. (1978): Distribution of 10 m snow temperature in Mizuho Plateau. Mem. Natl Inst. Polar Res., Spec. Issue, **7**, 63–71.

SATOW, K. and WATANABE, O. (1985): Net accumulation and oxygen isotope composition of snow on Mizuho Plateau, Antarctica. Ann. Glaciol., **6**, 300–302.

SATOW, K. and WATANABE, O. (1990): Seasonal variation of oxygen isotopic composition of firn cores in the Antarctic ice sheet. Ann. Glaciol., **14**, 256–260.

SCHOLANDER, P. F., DANSGAARD, W., NUTT, D. C., DE VRIES, H., COACHMAN, L. K. and HEMMINGSEN, E. A. (1962): Radio-carbon age and oxygen-18 content of Greenland icebergs. Medd. Grønl., **165**, 1–26.

SCHWERDTFEGER, W. (1975): The effect of the Antarctic Peninsula on the temperature regime of the Weddell Sea. Mon. Weather Rev., **103**, 45–51.

WATANABE, O., FUJII, Y. and SATOW, K. (1988): Depositional regime of the katabatic slope from Mizuho Plateau to the coast, East Antarctica. Ann. Glaciol., **10**, 188–192.

(Received March 6, 1991; Revised manuscript received June 6, 1991)