Stable isotopes in daily precipitation at Dome Fuji, East Antarctica

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Abstract

Daily precipitation samples for stable isotope analysis were collected throughout 2003 at Dome Fuji Station, inland East Antarctica. Stable isotopes show significantly depleted values with a large seasonal variability, which have never been obtained. Temporal changes in δ–T relation and d–excess are consistent with those found in geographical distribution. Precipitation was obtained almost everyday, though the amounts were quite small (27.6 mm water equivalent (w.e.) annual total and 0.08 mm w.e. daily average). Half of the annual precipitation was accumulated by only 11 events (18 days) without seasonality. Since the precipitation events occurred under warmer circumstances, the precipitation–weighted temperature, which should be related directly to the isotopes, was significantly warmer than the mean annual surface temperature, which has usually been adopted as isotopic thermometer. This study provides significant information to understand present–day seasonality of precipitation and its isotopic composition in inland Antarctica. **Citation:** Fujita, K., and O. Abe (2006), Stable isotopes in daily precipitation at Dome Fuji, East Antarctica, *Geophys. Res. Lett., 33*, L18503, doi:10.1029/2006GL026936.

1. Introduction

Water stable isotopes ($\delta^{18}O$ and δD) constitute the most fundamental parameter of a temperature index in ice core studies. Many geographical relationships have been established between the temperature at a depth of 10 m, which is equivalent to the mean annual surface temperature, and stable isotopes of surface snow/firns, and these have been applied to the interpretation of stable isotope records in ice cores [e.g., *Petit et al.*, 1999; *Watanabe et al.*, 2003; *EPICA Community Members*, 2004]. Despite various investigations of stable isotopes in surface snow/firn and 10–m temperature, we have little information on that of fallen snow in the interior of Antarctica, where extraction of deep ice cores has been conducted or is now being planned. To date, only *Jouzel et al.* [1983] and *Motoyama et al.* [2005] have reported temperature–$\delta^{18}O$ relations for fallen precipitation (not surface snow or firn) in the Antarctic interior, the South Pole, and Dome Fuji. However, their results were insufficient to evaluate the effect of precipitation seasonality because the precipitation amounts were not measured. In addition, deuterium excess (defined as $d = \delta D - 8\delta^{18}O$ [*Dansgaard*, 1964], hereinafter referred to as d–excess) is a unique parameter that is derived from water isotopes. The d–excess value reflects kinetic fractionation effects during evaporation at the ocean surface and snow formation, and can be used as an indicator of sea surface temperature (SST), relative humidity and wind speed at the water vapor source areas [*Merlivat and Jouzel*, 1979].

However, values of d-excess in an annual suite of daily precipitation samples have never been reported from Antarctica, to our knowledge. This study reports air temperature, daily precipitation, and its stable isotope contents at Dome Fuji, east Antarctica throughout the year 2003 (77°19'S, 39°41'E, 3810 m asl).

2. Sampling and Analysis

Precipitation samples were collected in two plastic containers (0.53 × 0.35 m^2) placed on the 4–m high roof of the Dome Fuji station and weighed every day in the period from 5 Feb. 2003 to 20 Jan. 2004. This sampling height assured no influence of surface–drifted snow [*Nishimura and Nemoto*, 2005]. Since the collected snow was too little for the analysis in many cases, accumulated snow on the roof was also added to the samples. Snow on the roof was swept clean at every sampling. Samples were packed in bottles and brought to Japan in a frozen state. Stable isotope ratios were analyzed by the CO_2–H_2O/H_2–H_2O equilibrium method with a mass spectrometer (Finnigan DeltaPlus) operated by the Hydrospheric Atmospheric Research Center of Nagoya University [*Members of Management Committee of Analytical System for Water Isotopes at HyARC*, 2005]. SMOW/SLAP calibration for each measured value was made by inter–/extrapolating a linear relationship between two working standards as seawater (–0.07‰ for $\delta^{18}O$, +0.8‰ for δD) and Antarctic water (–54.69‰ for $\delta^{18}O$, –424.7‰ for δD), whose accuracy was checked with isotopically intermediate water (–9.48‰ for $\delta^{18}O$, –63.0‰ for δD). The analytical precision of $\delta^{18}O$ (0.05‰) and δD (0.5‰) assure the high accuracy of individual deuterium excess measurements (quadratic analytical error of 0.64‰).

3. Delta Diagram

Figure 1 shows $\delta^{18}O$ and δD variations in individual precipitation. The lowest values of $\delta^{18}O$ and δD are notably depleted as –81.9‰ and –595.5‰, respectively, which are the isotopically lightest water ever collected on Earth's surface, to our knowledge. The accuracy of these highly depleted isotopic values was confirmed by validating the linearity according to the method by *Meijer et al.* [2000], in which we found no significant difference against the extrapolation using the conventional SMOW/SLAP calibration [*Gonfiantini*, 1978]. Stable isotopes show significant seasonal variability (49‰ for $\delta^{18}O$, 292‰ for δD) in contrast with values recorded in the deep ice core (12‰ for $\delta^{18}O$, 74‰ for δD) [*Watanabe et al.*, 2003]. This is due to the ice core sampling interval and isotopic diffusion in the firn/ice [e.g., *Johnsen*, 1977; *Whillans and Grootes*, 1985; *Johnsen et al.*, 2000].

4. Isotope and Temperature (δ–T Relation)

Seasonal change in $\delta^{18}O$ in daily precipitation is highly consistent with that of daily mean air temperature (Figures 2a). Figure 3 shows temporal δ–T relation (r=0.887 with a 99% significance level) in this study with geographical δ–T relations, which were obtained by isotopes in surface snow and 10–m snow temperature. All lines yield lower temperatures from the same or higher $\delta^{18}O$ from the same temperature than that from the present study. A part of this discrepancy may be caused by surface cooling due to strong inversion in winter. The 10–m depth temperature (–57.7 °C [*Motoyama et al.*, 2005]) at the station was cooler than the annual averages of air temperature at 1.5 m height (–55.0 °C in 1997 [*Hirasawa et al.*, 1999]; –54.8 °C in 2003, this study). It is unclear what causes the rest of the discrepancy. A sensitivity of $\delta^{18}O$ to temperature (δ–T gradient, $\delta^{18}O/dT$=0.78‰ °C^{-1}) in this study, however, is nicely consistent with those in the previous studies (0.76 to 0.85‰ °C^{-1}). This implies that the relative changes in the paleo–temperature of the ice core could be described by the geographical δ–T relation even in the seasonal time scale. On the other hand, a δ–T gradient obtained by *Motoyama et al.* [2005] (0.47‰ °C^{-1}), which only dealt with fallen snow and air temperature, was less than that in this study. Since their samples were obtained at the snow surface, whereas ours were collected 4 m higher, their δ–T relation might have been skewed by mixing with surface–drifted snow.

The δ–T relation clearly differs after the abrupt warming event in early November (Figure 2a). Figure 3 shows that the δ–T relation in summer (warming phase) is clearly lower in $\delta^{18}O$ than that in autumn (cooling phase). It implies that we obtained the isotopically lighter snow in summer than that in autumn even under the same temperature condition. Since the stable isotopes should be associated with the temperature where precipitation was formed, this discrepancy may be due to the different height of the top of inversion layer between two seasons. Although we unfortunately have no validation data, *Motoyama et al.* [2005] showed a rather steep δ–T gradient when they adopted the temperature at the top of inversion layer. For more understanding, we have to deal with δ–T relations in fallen snow, accumulated snow and ice cores.

5. Deuterium Excess

The d–excess in individual precipitation shows a pronounced seasonal cycle (higher in winter, lower in summer) with extremely large amplitude (Figure 2b) compared with that in the ice core (9‰ [*Uemura et al.*, 2004]). Figure 4 shows the relation between δD and d–excess in the precipitation with a fitting curve obtained from the International Trans–Antarctica Expedition [*Dahe et al.*, 1994]. Although the data from the surface snow are limited to more than –450‰ in δD [*Petit et al.*, 1991; *Dahe et al.*, 1994], the fitting curve well represents an increased tendency of d-excess in a colder environment (smaller δD). *Petit et al.* [1991] modeled the d–excess in surface snow considering the kinetic evaporation on the ocean at the different latitudes and assuming a supersaturation function for the formation of snow. They explained that the snow with higher d–excess was mostly originated from the mid–latitude with rapid evaporation, while the lower d–excess was caused by the additional vapor from the high latitude ocean with colder surface temperatures and higher relative humidity. The seasonality of d–excess (higher in winter, lower in summer) seems to be consistent with the explanation by *Petit et al.* [1991].

6. Effect of Precipitation Events

It has been pointed out that changes in precipitation seasonality between glacial and inter–glacial stages could significantly affect the interpretation of the isotopic temperature in the ice cores in Greenland [e.g. *Steig et al.*, 1994; *Werner et al.*, 2000]. With Antarctica, on the contrary, a model study suggested that the impact of changing seasonality has been limited [*Delaygue et al.*, 2000]. In the context of interpretation of ice core signals, therefore, the precipitation amount is the most significant factor in determining whether or not the signals of water isotopes were preserved in the ice core. Figure 2a also shows daily amounts of precipitation. Precipitation was obtained almost daily (339 days) during the observation period from 5 Feb. 2003 to 20 Jan. 2004 (349 days). The annual amount, 27.6 mm w.e., which was consistent with the stake measurements (27.5 ± 15.7 mm w.e. obtained from the change in surface level as 96 ± 49 mm and the surface snow density as 288 ± 17 kg m^{-3} for the period from 31 Jan. 2003 to 15 Jan. 2004). Most precipitation (321 days) fell in the form of "diamond dust" (ice crystal) precipitation from clear skies and accounted for half of the annual total (53%) based on a criterion such as the average (0.081 mm w.e.) plus one σ of the standard deviation (0.19 mm w.e.) of daily amount. The remainder (47%) was accumulated by only 11 events (18 days). In Figure 2, precipitation events seem to have occurred intermittently without any seasonal biases.

The fraction of precipitation amount implies that the half of annual signature in ice or snow will be provided by the 11 events. In order to assess what meteorological conditions caused these events and would be preserved in ice, meteorological variables and stable isotopes are weighted by the daily precipitation amount (Table 1). It is obvious that the "heavy snowfall" at Dome Fuji occurred under conditions such as higher air temperature, stronger wind speed, and higher air pressure. This is consistent with the previous studies, revealing that high–pressure blocking could be important for the vapor transfer to the Antarctic interior [*Enomoto et al.*, 1998; *Hirasawa et al.*, 2000; *Massom et al.*, 2004]. The average d–excess of heavy snowfall (10.7‰), which is close to that of the meteoric water line (10‰), suggests that the simple Rayleigh distillation process might form snow with the direct vapor transfer from the coast. Since the isotopic values in snow are that of precipitation, needless to say, the δ–T relation should be established between isotopes and temperature, both weighted by the daily precipitation amount. Therefore, the heavy snowfall under warm conditions leads to about a 5 °C warmer "precipitation–weighted" annual air temperature (–49.1 °C) than the arithmetic average (–54.8 °C). In addition, since the 10–m temperature (–57.0 °C) resulted from that of the surface, which is colder than the air temperature, the difference will increase up to 8 °C.

7. Concluding Remarks

In inland Antarctica, few observations have been made with respect to the water isotopes in fallen snow due to the difficulty in overwintering. While we have only one year of observations, daily samples show extreme depleted values and large seasonal variability in water isotopes. Our results with respect to the δ–T relation and the relation between δD and d–excess could be decisive evidence in support of the geographically obtained relations. On the other hand, the most unique feature of our dataset is the daily amount of precipitation, which has never been measured in inland Antarctica, since the isotopic temperature in the real sense of the term should be the precipitation–weighted temperature, while the geographical δ–T relation was that with the surface temperature. Our study suggests that the difference between isotopic temperature and surface temperature is 8 °C. This could have importants implication for isotope thermometry in ice core study.

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Table 1. Annual averages of air temperature, air pressure, wind speed and stable isotopes weighted by precipitation amount.

	All	$p < 0.27$	$p > 0.27$	Not weighted
Days	339	321	18	
Amount, mm w.e.	27.6	14.6	13.0	
Ratio, %	100	53	47	
Air temperature, °C	–49.1	–55.3	–42.2	–54.8
Air pressure, hPa	603	598	609	598
Wind speed, m s^{-1}	7.0	6.3	7.7	5.9
ΔD, ‰	–447.2	–471.8	–419.5	
$\delta^{18}O$, ‰	–57.7	–61.2	–53.8	
d–excess, ‰	14.3	17.6	10.7	

[a]Here p daily precipitation (mm w.e.)

Figure Legend

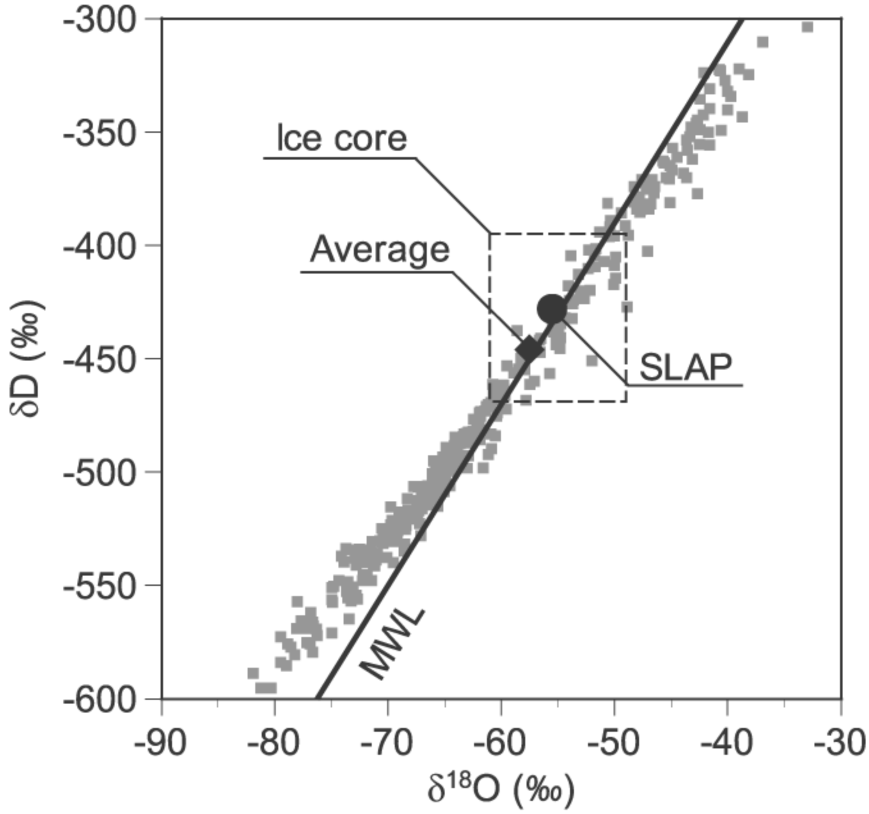
Figure 1. $\delta^{18}O$ and δD in individual precipitation at Dome Fuji from February 2003 to January 2004 (gray dots) with meteoric water line (MWL [*Craig*, 1961]). Solid rhombus and circle denote precipitation weighted average and the standard light Antarctic precipitation (SLAP). Box with broken line denotes the range recorded in the ice core.

Figure 2. Seasonal changes in daily mean air temperature (thin line, a), $\delta^{18}O$ (gray dots, a) and daily precipitation (black bars, a) and deuterium excess (black dots, b) at Dome Fuji from February 2003 to January 2004.

Figure 3. Oxygen stable isotopes in individual precipitation versus daily mean air temperatures in autumn (green), winter (blue) and summer (red) at Dome Fuji. Solid rhombus denotes the precipitation–weighted average. Solid and broken lines are the regression lines for the δ–T relations in the present study and that of *Motoyama et al.* [2004] (M), respectively. Gray broken (L), black dotted (S), and gray solid (D) lines denote the regression lines for the geographical δ–T relations between surface snow and 10–m snow temperature presented by *Lorius and Merlivat* [1977], *Satow et al.* [1999], and *Dahe et al.* [1994], respectively.

Figure 4. Deuterium excess and δD in individual precipitation at Dome Fuji with a regression curve established for the surface snow, which was geographically obtained [*Dahe et al.*, 1994].

Figure 1



Ice core
Average
SLAP
MWL
δD (‰)
δ18O (‰)
-300
-350
-400
-450
-500
-550
-600
-90
-80
-70
-60
-50
-40
-30

Figure 2

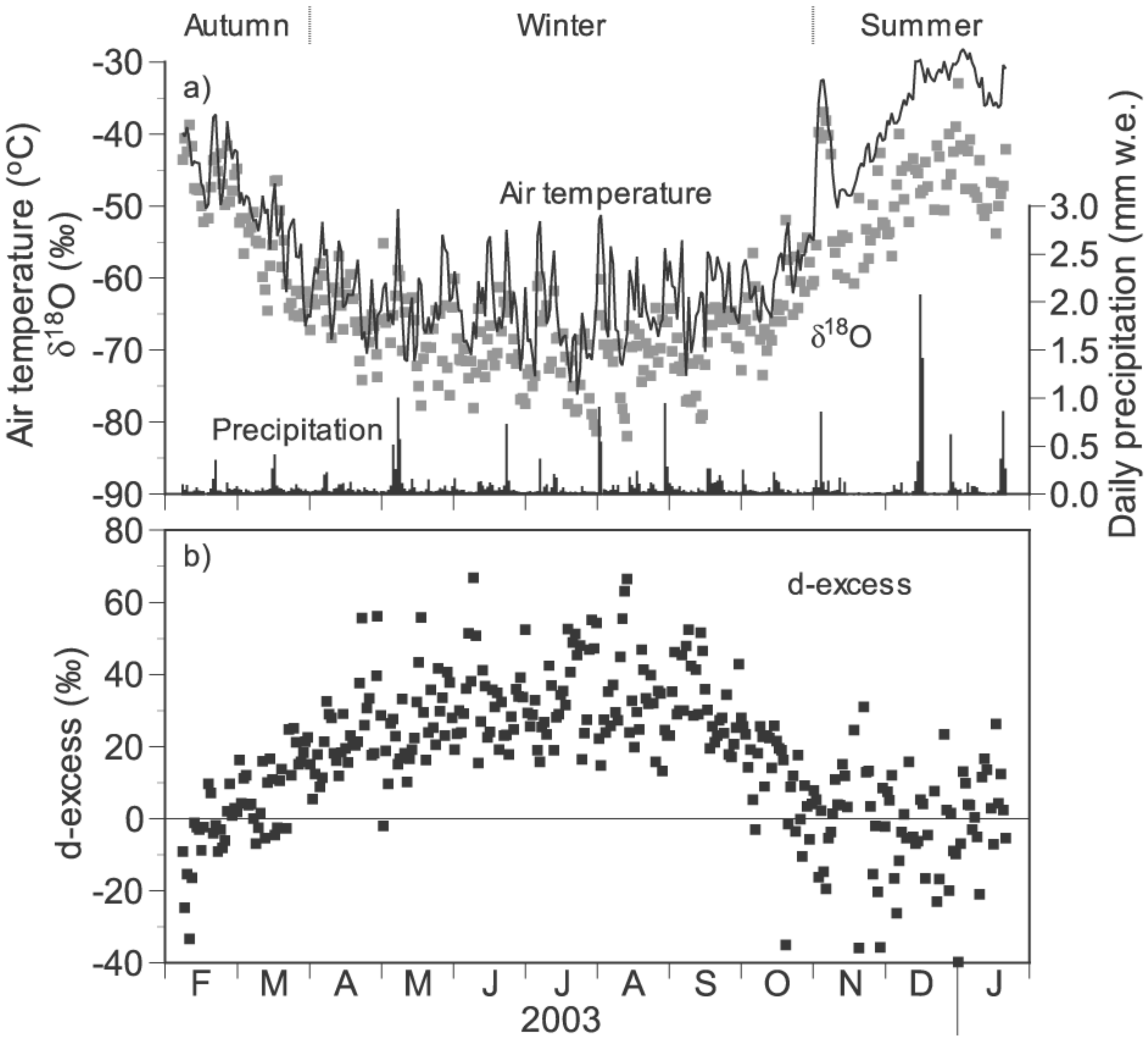
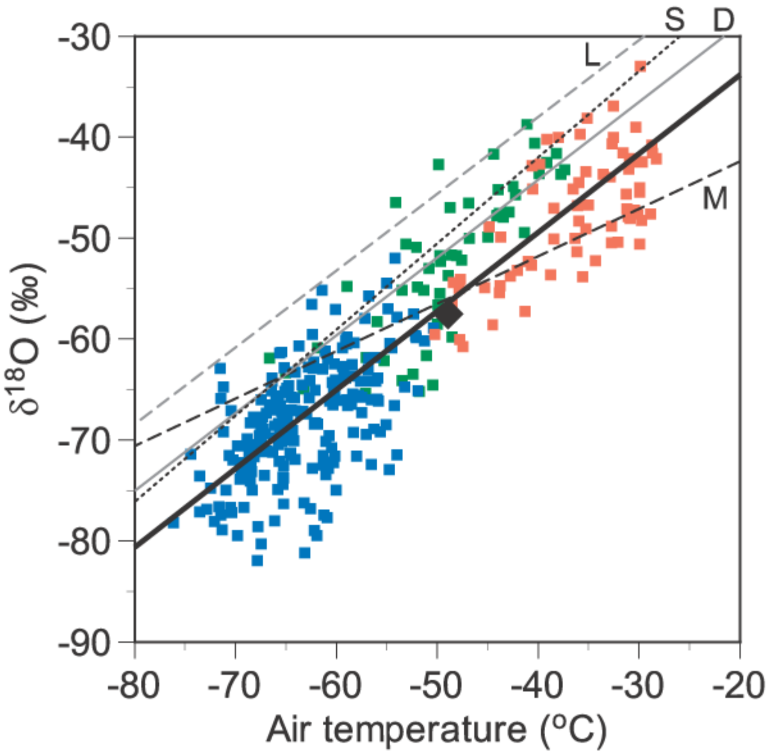
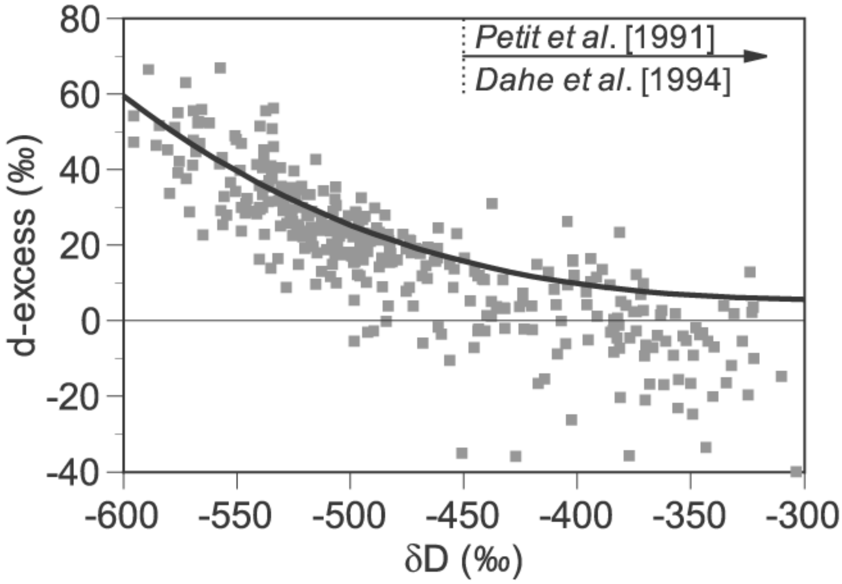

Autumn
Winter
Summer
a)
Air temperature
δ18O
Precipitation
Air temperature (°C)
δ18O (‰)
Daily precipitation (mm w.e.)
-30
-40
-50
-60
-70
-80
-90
3.0
2.5
2.0
1.5
1.0
0.5
0.0
b)
d-excess
d-excess (‰)
80
60
40
20
0
-20
-40
F
M
A
M
J
J
A
S
O
N
D
J
2003

Figure 3



S
D
L
M
-30
-40
-50
-60
-70
-80
-90
δ18O (‰)
-80
-70
-60
-50
-40
-30
-20
Air temperature (°C)

Figure 4



Petit et al. [1991]
Dahe et al. [1994]
d-excess (‰)
80
60
40
20
0
-20
-40
-600
-550
-500
-450
-400
-350
-300
δD (‰)