

7-15-2004

A Record of Atmospheric Co₂ During the Last 40,000 Years from the Siple Dome, Antarctica Ice Core

Jinho Ahn

Martin Wahlen

Bruce L. Deck

Ed J. Brook

Paul Andrew Mayewski

University of Maine - Main, paul.mayewski@maine.edu

See next page for additional authors

Follow this and additional works at: http://digitalcommons.library.umaine.edu/ers_facpub

 Part of the [Earth Sciences Commons](#)

Repository Citation

Ahn, Jinho; Wahlen, Martin; Deck, Bruce L.; Brook, Ed J.; Mayewski, Paul Andrew; Taylor, Kendrick C.; and White, James W.C., "A Record of Atmospheric Co₂ During the Last 40,000 Years from the Siple Dome, Antarctica Ice Core" (2004). *Earth Science Faculty Scholarship*. Paper 6.

http://digitalcommons.library.umaine.edu/ers_facpub/6

This Article is brought to you for free and open access by DigitalCommons@UMaine. It has been accepted for inclusion in Earth Science Faculty Scholarship by an authorized administrator of DigitalCommons@UMaine.

Authors

Jinho Ahn, Martin Wahlen, Bruce L. Deck, Ed J. Brook, Paul Andrew Mayewski, Kendrick C. Taylor, and James W.C. White

A record of atmospheric CO₂ during the last 40,000 years from the Siple Dome, Antarctica ice core

Jinho Ahn,¹ Martin Wahlen,¹ Bruce L. Deck,¹ Ed J. Brook,² Paul A. Mayewski,³ Kendrick C. Taylor,⁴ and James W. C. White⁵

Received 3 December 2003; revised 21 February 2004; accepted 13 April 2004; published 15 July 2004.

[1] We have measured the CO₂ concentration of air occluded during the last 40,000 years in the deep Siple Dome A (hereafter Siple Dome) ice core, Antarctica. The general trend of CO₂ concentration from Siple Dome ice follows the temperature inferred from the isotopic composition of the ice and is mostly in agreement with other Antarctic ice core CO₂ records. CO₂ rose initially at ~17.5 kyr B.P. (thousand years before 1950), decreased slowly during the Antarctic Cold Reversal, rose during the Younger Dryas, fell to a local minimum at around 8 kyr B.P., and rose continuously since then. The CO₂ concentration never reached steady state during the Holocene, as also found in the Taylor Dome and EPICA Dome C (hereafter Dome C) records. During the last glacial termination, a lag of CO₂ versus Siple Dome isotopic temperature is probable. The Siple Dome CO₂ concentrations during the last glacial termination and in the Holocene are at certain times greater than in other Antarctic ice cores by up to 20 ppm ($\mu\text{mol CO}_2/\text{mol air}$). While in situ production of CO₂ is one possible cause of the sporadic elevated levels, the mechanism leading to the enrichment is not yet clear. *INDEX TERMS:* 0325

Atmospheric Composition and Structure: Evolution of the atmosphere; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* CO₂, paleoclimate, Siple Dome

Citation: Ahn, J., M. Wahlen, B. L. Deck, E. J. Brook, P. A. Mayewski, K. C. Taylor, and J. W. C. White (2004), A record of atmospheric CO₂ during the last 40,000 years from the Siple Dome, Antarctica ice core, *J. Geophys. Res.*, 109, D13305, doi:10.1029/2003JD004415.

1. Introduction

[2] Understanding how the atmospheric concentration of CO₂ changed in the past in response to other changes in the climate system provides us with a better understanding of how current and future changes in the carbon cycle will influence our future climate. The concentration of CO₂ in the atmosphere during previous times can be determined by measurements made on the air trapped in ice cores [e.g., Delmas *et al.*, 1980; Neftel *et al.*, 1982; Fischer *et al.*, 1999; Petit *et al.*, 1999]. CO₂ records from Antarctic ice cores are considered to be representative of paleoatmospheric concentrations. Greenland ice cores are not useful for determining the paleoatmospheric concentration because of in situ production of CO₂ due to high dust content [Barnola *et al.*, 1995; Anklin *et al.*, 1995, 1997; Smith *et al.*, 1997a, 1997b; Tschumi and Stauffer, 2000].

[3] The Siple Dome ice core from West Antarctica was drilled from 1997 to 1999. The site is at 81.66°S, 148.82°W, at an altitude of 621 meters asl, with an annual mean temperature of -25.4°C and an accumulation rate of 12.4 g cm⁻² yr⁻¹ as water equivalent (Figure 1 and Table 1). The total depth of the core is 1003.8 m. The high accumulation rate at Siple Dome allows rapid climate changes to be more accurately preserved and permits more accurate assessment of the relative timing between ice-isotopic variations and of variations in occluded gases compared to the low accumulation rate sites like Vostok, Dome C, or Dome Fuji (Table 1). In this study, we compare the CO₂ record from the Siple Dome ice core for the last 40,000 years with CO₂ records from other Antarctic ice cores using common time scales based on the GISP2 gas age and correlation to Antarctica using CH₄ concentrations variations. We also examine the relative timing of the CO₂ increase and temperature change. The highest resolution CO₂ record from Law Dome covering only the last thousand years [Etheridge *et al.*, 1996], and the recent Dome Fuji CO₂ record over the last 320 kyr [Kawamura *et al.*, 2003] measured by the wet extraction method are not discussed.

2. Method and Timescales

[4] Measurements were made on 462 samples from 86 depths in the top 832 meters in the Siple Dome ice core.

¹Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

²Department of Geology and Program in Environmental Science, Washington State University, Vancouver, Washington, USA.

³Climate Change Institute, University of Maine, Orono, Maine, USA.

⁴Desert Research Institute, University of Nevada, Reno, Nevada, USA.

⁵Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder, Colorado, USA.



Figure 1. Location map of Antarctic ice cores referred to in the text.

These measurements span over the last 40,000 years. The ice core has a diameter of 13 cm. The outer 0.5 to 2 cm of the samples was removed with a band saw to reduce the possibility of contamination from present atmospheric CO₂ or postdrilling chemical reactions. The Siple Dome core samples contain bubbles and did not contain clathrates. Post collection temperature monitoring confirmed that the ice was kept below -15°C from the time it was removed from the drill site to arrival at Scripps Institution of Oceanography (SIO). The storing, cutting, and loading of samples into a mechanical crusher at SIO was done at -25°C . At most depths four to six ice samples, taken from a depth interval spanning 1 to 3 cm (mostly less than several years in ice age), were analyzed for each reported data point. At some depths samples of 6 to 12 cm depth intervals were used because of poor quality (extensive fracturing in the ice). Many fractures were observed below 500 m and the samples were more extensively trimmed in this region to assure sampling of unfractured ice. Contamination through undetected fractures results in higher CO₂ values due to high CO₂ concentration in the ambient air.

[5] For outliers in a group of samples cut from the same depth interval, we applied Grubb's test at the 95% confidence level to the suspected data. In this test a ratio of the difference between the outlier and the mean and the standard deviation of the data for the group was compared to a critical value [Iglewicz and Hoaglin, 1993]. We rejected results from 12 individual ice samples (usually the highest values) out of the total of 462 analyzed.

[6] The gas extraction and IR spectroscopic methods used are well established [Wahlen *et al.*, 1991; Smith *et al.*, 1997a, 1997b; Fischer *et al.*, 1999]. Occluded air was dry extracted by mechanical crushing of samples in a double walled crusher cooled using an ethanol-liquid nitrogen mixture at about -50°C . The liberated air was collected in cold traps chilled by closed cycle He refrigerators to a temperature of about 32 K. The frozen air samples held in the cold traps were liberated by heating and transferred to an IR absorption cell held at a constant pressure and temperature. IR absorption measurements were made several times on each gas sample with a tunable diode laser by scanning a single vibrational-rotational CO₂ absorption line at Doppler resolution in the R branch of the 4.3 μm CO₂ absorption band. To calibrate the instrument, measurements were made

with three air standards of precisely known CO₂ concentrations of 163, 240, and 330 ppm (± 0.01 ppm, C. D. Keeling, personal communication) that were introduced over three of the crushed ice samples, thus duplicating the crushing procedure. This calibration procedure was performed each day. A group of samples from the same depth interval were measured on the same day. The average standard deviation of the data of the samples from the same depth interval measured on the same day (5.9 ppm) is greater than the daily internal precision (1.7 ppm) measured on crushed ice samples with reference gas added. Considering the daily uncertainty in calibration and the reproducibility, we expect the internal precision to be better than 2 ppm when measured on different days for a group of samples from the same depth interval with constant CO₂ concentration among the samples. Directly introduced standards (not over ice) were run to check laser linearity and performance.

[7] The gas age dating of the Siple Dome core over the time period of 40 to 8.2 kyr B.P. is established by correlation of CH₄ data with those of the GISP2 ice core [Taylor *et al.*, 2004b; E. Brook *et al.*, manuscript in preparation, 2004]. The methods for CH₄ measurements are described by Brook *et al.* [2000, manuscript in preparation, 2004]. For ice younger than 8.2 kyr B.P. the age of the ice was determined by counting annual layers and the corresponding gas ages were assigned by subtracting the ice age – gas age difference (Δage) from the ice ages [Taylor *et al.*, 2004a]. The Δage was calculated with a firn densification model (Brook *et al.*, manuscript in preparation, 2004). The Δage is about 280 ± 80 years in the early Holocene, increasing to about 750 ± 220 years during the Last Glacial Maximum (LGM). The gas age of bubble ice varies according to ice bubble close-off depth. We estimate that the width of the age distribution is on the order of 10% of the Δage value [Goujon *et al.*, 2003].

3. Results

3.1. Data Quality

[8] Measurements were made over a period of 2.5 years at random depth intervals to eliminate the possibility that

Table 1. Characteristics of the Antarctic Ice Cores From Which CO₂ Gases Have Been Measured

Core Name	Mean Annual Temperature, $^{\circ}\text{C}$	Mean Accumulation Rate as Water Equivalent, $\text{g cm}^{-2} \text{ yr}^{-1}$	Elevation, m
Law Dome	$-22 \sim -19^{\text{a,b}}$	$60 \sim 110^{\text{b}}$	1390 ^b
Siple Dome	-25.4^{c}	12.4^{d}	621 ^c
Byrd ^f	-28	16	1530
Taylor Dome	-42^{e}	7^{h}	2374 ^h
EPICA Dome C	-54^{i}	3^{j}	3233 ^k
Vostok ^f	-55.5	2.3	3490
Dome Fuji ^l	-58	3.2	3810

^aEtheridge and Wooley [1989].

^bEtheridge *et al.* [1996].

^cSeveringhaus *et al.* [2001].

^dHamilton [2002].

^eTaylor *et al.* [2004b].

^fRaynaud *et al.* [1993].

^gWaddington and Morse [1994].

^hAs unit of cm ice equivalent per year [Steig *et al.*, 1998].

ⁱSchwander *et al.* [2001].

^jEPICA Dome C 2001-02 Science and Drilling Teams [2002].

^kTabacco *et al.* [1988].

^lDome-F Deep Coring Group [1998].

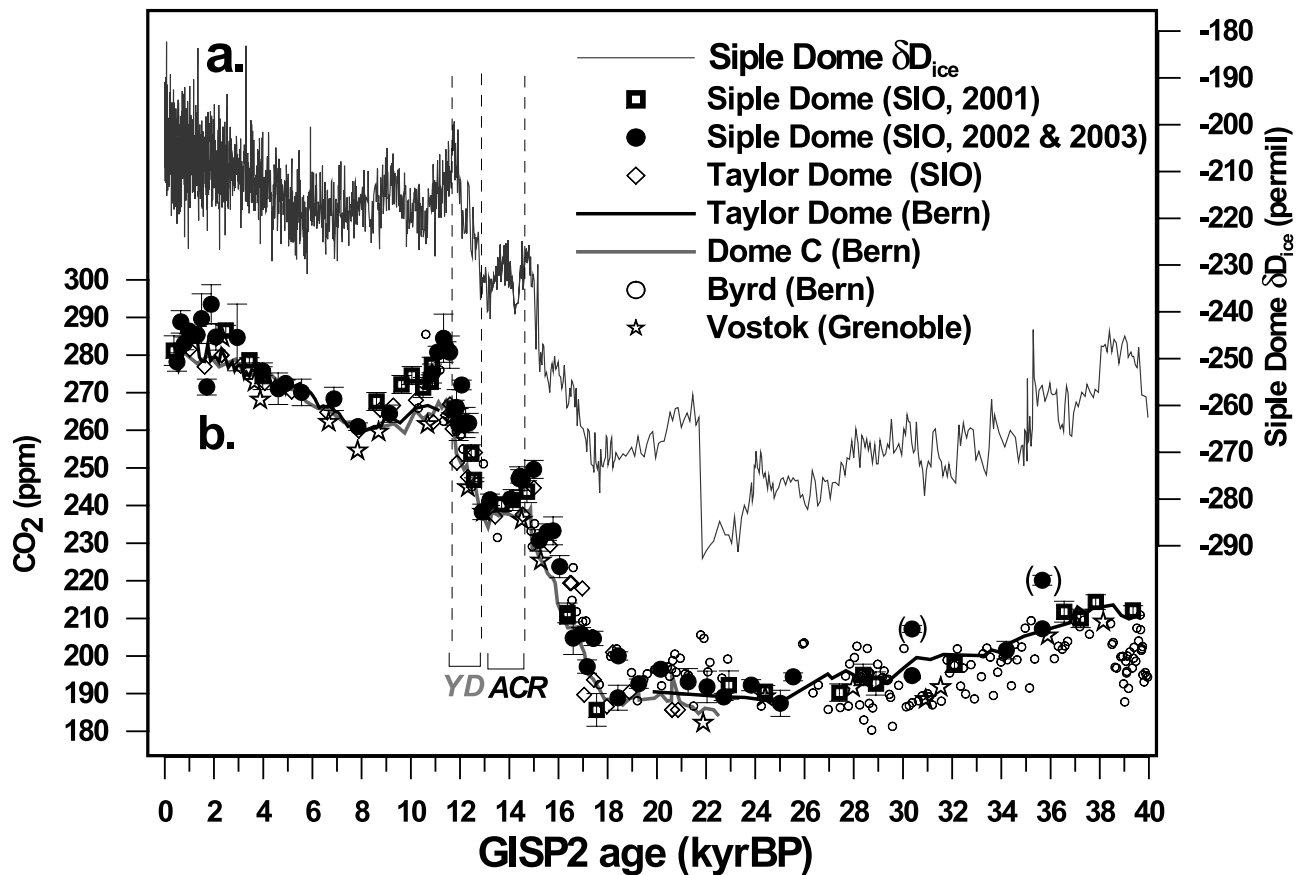


Figure 2. Antarctic ice core CO₂ plotted on GISP2 gas age scale. (a) Siple Dome δD_{ice} on ice age scale. (b) Ice core CO₂ records on synchronized gas age scale with GISP2 via CH₄. Shown are Vostok data [Petit *et al.*, 1999], EPICA Dome C [Monnin *et al.*, 2001; Flückiger *et al.*, 2002], Taylor Dome [Indermühle *et al.*, 1999, 2000; Smith *et al.*, 1999], and Byrd [Neftel *et al.*, 1988; Staffelbach *et al.*, 1991] and Siple Dome (this study). Error bars represent one standard error deviation of the replicate measurements at the same depth interval. The brackets indicate averages of two anomalously high values of the six samples from the same depth intervals. Taylor Dome gas ages of 40 to 20 kyr B.P. are from Brook *et al.* [2000]; Byrd gas ages are from Blunier and Brook [2001]; Vostok gas ages for 40 to 10 kyr B.P. are from Blunier *et al.* [1998]. The Vostok GT4 timescales [Petit *et al.*, 1999] are younger than those of GISP2 by about 1 kyr for the latter of the last termination and by up to 5 kyr during 40 to 20 kyr B.P. The Holocene depth-gas age scales of Vostok and Dome C are linearly interpolated between the youngest age points and synchronized gas age points in the early Holocene. Dome C gas ages for 17.2 to 11 kyr B.P. are synchronized with GISP2 in this study and for 22.5 to 17.2 kyr B.P. are extended from the synchronized gas age at 17.2 kyr B.P. by adding the depth-gas age intervals of the original paper [Monnin *et al.*, 2001]. YD, Younger Dryas; ACR, Antarctic Cold Reversal.

unnoticed analytical changes would create trends in the data. Measurements of Siple Dome CO₂ made in 2001 (black open squares) at SIO agree well with those made in 2002 and early 2003 (solid circles) as shown in Figure 2b.

[9] The results can be compared to other Antarctic ice cores as shown in Figure 2b. The CO₂ concentration of Dome C, Taylor Dome and Byrd cores were measured in Bern [Monnin *et al.*, 2001; Flückiger *et al.*, 2002; Indermühle *et al.*, 1999, 2000; Neftel *et al.*, 1988; Staffelbach *et al.*, 1991] and compare well with the SIO data. This is expected because Bern's gas extraction method (dry crushing) is similar to that at SIO.

[10] High accumulation rate provides a small width of gas age distribution and therefore a record of high temporal resolution. Similarly, t of small pieces of ice poten-

tially also improves temporal resolution. On the other hand, this potentially increases the scatter in the data since inhomogeneities are not smoothed out as they are in larger samples covering longer intervals of time [Smith *et al.*, 1997a]. The accumulation rate at Siple Dome is two and five times larger than that at Taylor Dome and Dome C, respectively. Thus the high accumulation rate at Siple Dome (Table 1) and the small sample size (4 to 6 cm³) used in the measurement at SIO may increase the scattering of the Siple Dome data. Sample sizes used in the Siple Dome CO₂ study at SIO are half of those used for Taylor Dome and Dome C at Bern. Some Taylor Dome samples were also measured at SIO (Figure 2b) and there is good agreement between the SIO and the Bern results, even though the volume of samples for a depth interval used at SIO was about one

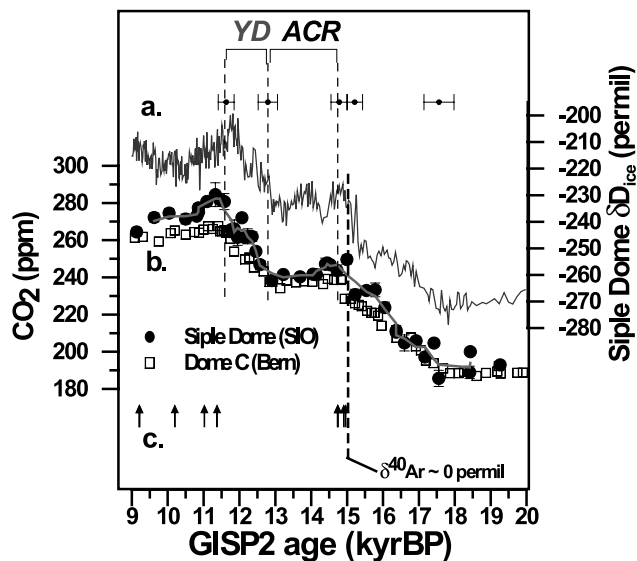


Figure 3. CO₂ change during the last Termination. (a) Siple Dome δD_{ice} on ice age scale. (b) CO₂ records from Siple Dome (solid circles) and Dome C (open squares) [Monnin *et al.*, 2001]. The line between Siple Dome CO₂ is the running average of three adjacent points. (c) Melt layers (vertical arrows) [Das, 2003]. The horizontal bars at top are gas age ranges around age tie points based on CH₄ records between Siple Dome and GISP2. The thick vertical dashed bar indicates where the argon and nitrogen isotopic anomaly occurs [Severinghaus *et al.*, 2003]. YD, Younger Dryas; ACR, Antarctic Cold Reversal.

fourth of what was used at Bern, where calibration was routinely done using reference gases from SIO at 251.7 ppm and 321.06 ppm [Indermühle *et al.*, 1999].

3.2. Trend of the Siple Dome CO₂ Record

[11] In general, the trends in the Siple Dome CO₂ record (solid circles and open squares in Figure 2b) follow temperature trends, indicated by δD_{ice} (Figure 2a), which is taken as a proxy for local temperature. The general time series of Siple Dome CO₂ concentration confirms previous studies in Antarctic ice cores (Figures 2 and 3). The Siple Dome CO₂ record shows a continuous decrease from 214 ppm at 38 kyr B.P. to 186 ppm at LGM (~18 kyr B.P.) and then a rapid increase up to 247 ppm during the early part of the last termination. It is important to note that the CO₂ increase is reversed during the Antarctic Cold Reversal (15 to 13 kyr B.P.) reaching a local minimum of 239 ppm, which has been observed in the Dome C, Taylor Dome and Byrd records. After the Antarctic Cold Reversal, Siple Dome CO₂ increases again reaching up to 284 ppm at the beginning of the Holocene (11.5 kyr B.P.). This increase occurs during the Younger Dryas interval as shown in the Dome C record [Monnin *et al.*, 2001]. During the Holocene, the Siple Dome CO₂ concentrations decrease to a local minimum of 261 ppm at about 8 kyr B.P., and then increase to 285 ppm in the late Holocene (mean of the scattered values). There is good agreement of this local minimum at about 8 kyr B.P. between the different Antarctic cores from Siple Dome, Taylor Dome, Dome C and Vostok. The CO₂ concentration never reaches a steady state during the Holo-

cene after the end of the last termination as was also found in the Taylor Dome and Dome C records [Indermühle *et al.*, 1999; Flückiger *et al.*, 2002].

[12] Figure 3 shows an enlarged portion of Figure 2 covering the last termination. Again, Siple Dome CO₂ follows the temperature proxy (δD_{ice}) as seen in other Antarctic ice cores. For most of the record, the Siple Dome CO₂ time trend is almost the same as that of the high resolution Dome C record.

[13] However, at the depth (677.61 m) corresponding to around 15 kyr B.P., CO₂ in Siple Dome is higher than in Dome C by about 21 ppm. We believe that this anomalous CO₂ value is suspicious as an atmospheric CO₂ record because of the following two reasons. First, near the depth of the anomalously high CO₂ value (~20 cm apart in depth), the δ⁴⁰Ar and δ¹⁵N of N₂ values reach atmospheric values, indicating there was no diffusive column and a possible hiatus in deposition [Severinghaus *et al.*, 2003]. Second, the difference of 21 ppm is too large to be explained by age uncertainties. The anomaly occurs at a greater depth than that corresponding to the beginning of Antarctic Cold Reversal (defined by the rapid increase in CH₄ concentration from Siple Dome ice, as defined in the Dome C ice core, where abrupt CO₂ and CH₄ increases happened [Monnin *et al.*, 2001]). Thus the age uncertainty at this depth does not affect the CO₂ difference between Siple Dome and Dome C significantly (<5 ppm).

[14] Except for this anomalous period, we calculate the rates of CO₂ change and time lag of CO₂ compared to temperature. During the last termination, CO₂ changed at the rate of 19.1 ppm/kyr from 17.7 to 15 kyr B.P., -5.2 ppm/kyr during the Antarctic Cold Reversal (15 to 13 kyr B.P.) and 26.8 ppm/kyr from 13.0 to 11.3 kyr B.P., respectively. These values are similar to CO₂ changes in the Dome C record [Monnin *et al.*, 2001].

3.3. Phase Relationship Between Changes in CO₂ and Siple Dome Temperature

[15] To compare the phasing of changes in CO₂ and surface temperature (using δD_{ice} as a temperature proxy), we interpolated the CO₂ and δD_{ice} data on a 10-year spacing. We calculated the change in CO₂ and δD_{ice} (dCO₂/dt and d(δD_{ice})/dt) for 10-year intervals and smoothed them by averaging over time windows ranging from 0 to 500 years. The correlation coefficient between the dCO₂/dt and d(δD_{ice})/dt was then calculated for different lag times and for different degrees of smoothing. The maximum correlation coefficients were obtained with a 210 ~ 330 year lag of dCO₂/dt behind d(δD_{ice})/dt with a smoothing of 200 ~ 500 years as shown in Figure 4a. Several maxima in correlation coefficients for different time lags are observed over less than 200-year windows, possibly due to the average spacing of 230 years in the CO₂ data. To check the sensitivity of the time lag by the uncertainties in CO₂ concentration and Δage, we carried out Monte Carlo simulations for CO₂ concentrations in two conditions, namely maximum Δage (estimated Δage + uncertainty) and minimum Δage (estimated Δage - uncertainty). For each situation, we produced 3000 different sets of CO₂ concentrations, which vary randomly with Gaussian propagation in their uncertainties. After interpolation and smoothing both dCO₂/dt and d(δD_{ice})/dt with

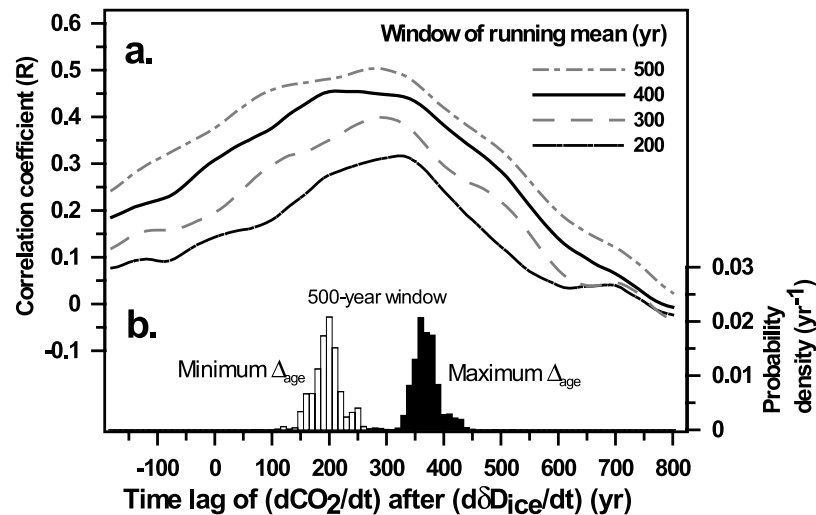


Figure 4. Time lag analysis of (dCO₂/dt) after (dδD_{ice}/dt) in the Siple Dome ice core during the last termination. (a) Correlation coefficients for different time lags after averaging data with windows of 200 ~ 500 years. (b) Histograms of the time lags after Monte Carlo simulation for CO₂ concentrations in two situations, maximum Δ_{age} and minimum Δ_{age}. For each situation, 3000 different sets of CO₂ concentrations were generated and used. The derived dCO₂/dt and d(δD_{ice})/dt were smoothed with 500-year window for each data set.

500-year window, maximum correlation coefficients were obtained with a 369 ± 23 years lag (mean $\pm 1\sigma$) for maximum Δ_{age} and 196 ± 25 (mean $\pm 1\sigma$) for minimum Δ_{age} as seen in Figure 4b. The time lags for CO₂ behind temperature are greater than the uncertainty of the Δ_{age} of 80 years at the end of the last termination but close to 220 years at LGM. The time lags roughly agree with those of Fischer *et al.* [1999] (600 ± 400 years during the last three terminations in Byrd, Taylor Dome and Vostok records) and are slightly less than the value proposed by Monnin *et al.* [2001] (410 years during the last termination in Dome C record). Indermühle *et al.* [2000] found higher values (1200 ± 700 years) for the period 60 to 20 kyr B.P. in the Taylor Dome record, as did Caillon *et al.* [2003] (800 ± 200 years) across termination III in the Vostok record. Although the correlation method discussed above suggests that changes in surface temperature at Siple Dome could lead changes in the concentration of atmospheric CO₂ by ~ 300 years, this lead is small relative to both our sampling interval and possible systematic error in Δ_{age}, for example due to inaccuracies in estimating past accumulation rates, which are derived from a thermodynamic model employing temperatures calculated from the δD_{ice} record (Brook *et al.*, manuscript in preparation, 2004). Our main conclusion is therefore that a lead of CO₂ versus Siple Dome temperature is unlikely, a lag of CO₂ versus Siple Dome temperature is likely, and that our results provide strong support for previous suggestions of a close link between Antarctic temperature and CO₂ change during the deglaciation.

4. Possible Mechanisms for In Situ CO₂ Production

[16] In some depth intervals the CO₂ concentrations in Siple Dome ice are than in the Vostok, Taylor

Dome and Dome C cores (Figures 2 and 3). These differences are up to 20 ppm greater (e.g., at around 11 kyr B.P.). One possible explanation for these differences is uncertainty in the age scales, particularly at times when CO₂ was changing. For example, during the two periods of rapid CO₂ increase during the last termination, an offset of 300 years between otherwise identical records would produce a CO₂ difference of 10 ppm. This effect may explain the differences between the Siple Dome versus the Dome C and Siple Dome versus the Taylor Dome cores (Figure 5c). The low CO₂ values of the Byrd ice core at about 39 kyr B.P. can be compared to low values in Taylor Dome at about 42 kyr B.P. (not shown in Figure 2) on the GISP2 age scale [Indermühle *et al.*, 2000]. However, elevated CO₂ levels in the Siple Dome at times of relatively little change in CO₂ (for example, during the Antarctic Cold Reversal or in the earliest Holocene) cannot be attributed to timescale uncertainties. Interestingly, most of the cold period (40 ~ 23 kyr B.P.) CO₂ data from the Siple Dome ice shows little difference in CO₂ when compared to other cores.

[17] As mentioned above, large variations of atmospheric CO₂ concentrations between Antarctic ice core sites are unlikely, prompting us to search for another explanation for the differences between the Siple Dome CO₂ and other records. To examine the possibility and the mechanisms of CO₂ production, we check the CO₂ difference between Siple Dome and Taylor Dome or Dome C (Figure 5c). We call this “excess CO₂” although we cannot rule out the possibility of CO₂ consumption in other ice cores by the interaction between CO₂ in the bubbles and the carbonates in the ice (i.e., $\text{CO}_2 + \text{CO}_3^{2-} + \text{H}_2\text{O} \rightarrow 2\text{HCO}_3^-$) [Nefel *et al.*, 1982].

[18] The excess CO₂ is high at depth of 100 to 330 m (0.4 to 3.5 kyr B.P.) and 560 to 640 m (9.5 to 12.5 kyr B.P.) but is within the experimental uncertainty at depths >708 m

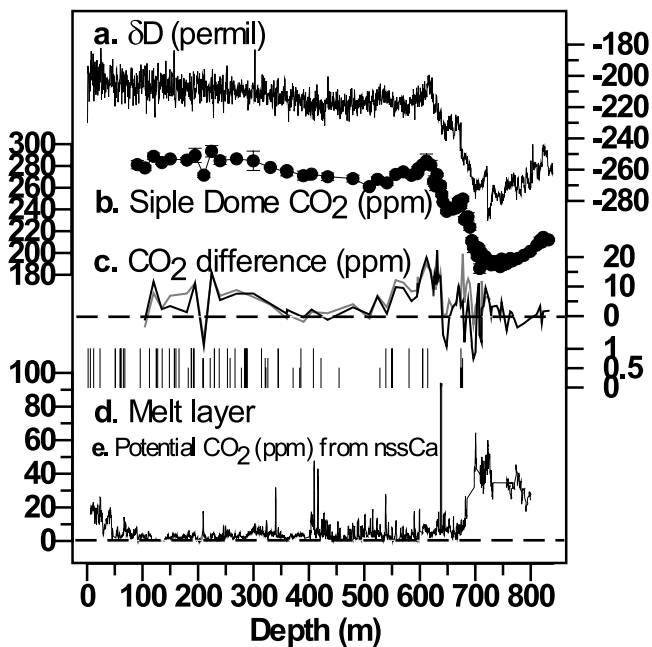


Figure 5. Comparison of possible processes of the excess CO₂ in Siple Dome ice cores on depth scale. (a) Siple Dome δD_{ice} . (b) Siple Dome CO₂. (c) CO₂ difference between Siple Dome and Taylor Dome (solid line) or Dome C (shaded line). The dashed horizontal line represents 0. (d) Melt layers [Das, 2003]. The lengths of bars indicate the confidence level. 1, sure; 0.75, probable; 0.5, possible. (e) Potential CO₂ from acid-carbonate reaction. The dashed horizontal line represents 0. Non-sea-salt Ca (nssCa) was assumed to have been in the form of CaCO₃ and totally reacted with excess H⁺. Considering total gas content in the unit gram of ice [Severinghaus *et al.*, 2003], the CO₂ produced by the reaction was converted to a concentration change of CO₂.

(17.5 kyr B.P.). The Siple Dome ice samples are more fractured than Taylor Dome samples below about 500 m (about 8 kyr). One possibility is that the CO₂ in the core might be compromised by air entering fractures in the core that reseal after the ice reaches the surface, during transportation and storage. However, there are high excess CO₂ values in the late Holocene Siple Dome ice where fracturing is minor, and low excess CO₂ in glacial ice where Siple Dome ice is highly fractured. Moreover, correlations between the scattering of data from adjacent samples and excess CO₂ does not support the possibility of ambient air contamination. The above observations imply the possibility that some of the artifacts in Siple Dome CO₂ records are related to in situ CO₂ production in the ice.

[19] Possible CO₂ production mechanisms include (1) carbonate-acid reaction [Delmas, 1993; Anklin *et al.*, 1995, 1997; Barnola *et al.*, 1995; Smith *et al.*, 1997a, 1997b], (2) oxidation of organic compounds abiologically [Tschumi and Stauffer, 2000], or biologically [Campen *et al.*, 2003], and (3) snowmelting-refreezing [Nefstel *et al.*, 1983; Stauffer *et al.*, 1985].

[20] We have calculated the potential CO₂ produced by the carbonate-acid reaction between CaCO₃ and H⁺ [Nefstel

et al., 1988], as shown in Figure 5e, using the non-sea-salt Ca (nssCa) ion content assuming all of the nssCa is from CaCO₃ and that all CaCO₃ reacts to produce CO₂. This source of potential CO₂ is too low to produce the excess CO₂ observed during the Holocene and shows little correlation with the excess CO₂ data (Figure 5c). Moreover, electric conductivity measurements (ECM, proxy for H⁺) do not show any significant change at the depth intervals of high excess CO₂ in Figure 5c. Thus it is unlikely that a carbonate-acid reaction has affected the Siple Dome CO₂ record.

[21] Oxidation of organic compounds has been proposed to be at least as important as acid-carbonate reactions for CO₂ production (e.g., 2H₂O₂ + HCHO → 3H₂O + CO₂) [Tschumi and Stauffer, 2000]. Organic acid concentrations in Siple Dome ice core have not yet been reported. H₂O₂ is one of the important oxidants of organics in ice. The top 100 m of Siple Dome ice core shows concentrations near or below the detection limits of ~0.02 μM H₂O₂ except at the 0 to 2.5 m depth [McConnell, 1997]. This H₂O₂ concentration corresponds to a potential CO₂ production of less than 5 ppm assuming an adequate supply of organic acids, which does not easily explain the 20 ppm excess CO₂. CH₃COO⁻ and HCOO⁻ can act as other oxidants [Tschumi and Stauffer, 2000]. Another possible CO₂ production mechanism is respiration of microorganisms (consuming organic acids and producing CO₂) within the ice [Campen *et al.*, 2003]. Natural organic acids and other organic materials have much lower values of $\delta^{13}\text{CO}_2$, approximately -25‰, compared to atmospheric $\delta^{13}\text{CO}_2$ (preindustrial value of about -6.5‰) and CaCO₃ (0 ~ 4‰). Thus precise $^{13}\text{CO}_2$ values could be used to investigate the sources of excess CO₂. For example if the early Holocene CO₂ record has excess CO₂ values of 20 ppm derived from organic materials, it would reduce the $\delta^{13}\text{CO}_2$ value by about 1‰. However, $^{13}\text{CO}_2$ analyses in the Siple Dome ice core have been hampered by the contamination of the ice by drilling fluid, n-butyl acetate, which in the mass spectrometer lead to fragmentation interference with m/z = 45 [Ahn *et al.*, 2001].

[22] CO₂ can be considerably enriched in frozen melt layers due to the high solubility of CO₂ in meltwater [Nefstel *et al.*, 1983]. At Dye 3, Greenland, melt layers contribute about 7% by volume at today's climate conditions and show mean CO₂ concentration as much as 1500 ppm [Stauffer *et al.*, 1985]. The annual mean snow temperature of Siple Dome is -25.4°C, the highest among the Antarctic ice cores discussed in this paper [Severinghaus *et al.*, 2001], and occasional surface melting occurs during the summer, resulting in thin bubble free layers in the ice core. These melt layers can be detected visually, see arrows in Figures 3c and bars in Figure 5d [Das, 2003]. The ice samples measured for the Siple Dome CO₂ did not include visible melt layers. However, it is likely that small melt layers would not be detected visually, particularly deeper in the core where ice flow has thinned the layering. The mode of excess CO₂ is only weakly associated with that of melt layers (Figures 5c and 5d). Alternative possibilities beside warm temperature and the coastal location of the Siple Dome (Figure 1 and Table 1) include higher ambient temperatures during the austral summer (often being substantially higher than the mean annual temperature of

–25.4°C), combined with high sea salt content, resulting in CO₂ contamination.

5. Conclusion

[23] We present the CO₂ record of air occluded over the last 40,000 years in the Siple Dome ice core, Antarctica. The general time series of Siple Dome CO₂ concentration is similar to previous studies in other Antarctic ice core CO₂ records. Siple Dome ice also shows that surface temperature inferred from δD_{ice} correlates well with CO₂ concentration as shown in other Antarctic ice cores. During the last termination, it is likely that the change of the Siple Dome CO₂ concentrations lags the Siple Dome temperature change. Despite similarities with other Antarctic ice cores, the Siple Dome ice shows higher CO₂ concentrations than those in other Antarctic ice cores at some depth intervals, which may be due to in situ production in the ice. The cause of these elevated concentrations is not known with certainty. CO₂ production due to surface melting is the leading hypothesis, but the evidence is not definitive.

[24] **Acknowledgments.** We wish to thank Jeff Severinghaus, Sarah Das, Richard Alley, Joe McConnell, and Jihong Cole-Dai for advice and for providing unpublished data. Anonymous reviewers provided constructive comments. Staff at the National Ice Core Laboratory is thanked for the assistance with core processing. This work was supported by the Office of Polar Program of the NSF (NSF OPP 99-80619).

References

- Ahn, J., M. Wahlen, and B. Deck (2001), Measurement of atmospheric CO₂ trapped in the Siple Dome ice core, *Eos Trans. AGU*, 82(47), Fall Meet. Suppl., Abstract A51F-0105.
- Anklin, M., J.-M. Barnola, J. Schwander, B. Stauffer, and D. Raynaud (1995), Processes affecting the CO₂ concentrations measured in Greenland ice, *Tellus, Ser. B*, 47, 461–470.
- Anklin, M., J. Schwander, B. Stauffer, J. Tschumi, A. Fuchs, J.-M. Barnola, and D. Raynaud (1997), CO₂ record between 40 and 8 kyr B.P. from the Greenland Ice Core Project ice core, *J. Geophys. Res.*, 102, 26,539–26,545.
- Barnola, J. M., M. Anklin, J. Porcheron, D. Raynaud, J. Schwander, and B. Stauffer (1995), CO₂ evolution during the last millennium as recorded by Antarctic and Greenland ice, *Tellus, Ser. B*, 47, 264–272.
- Blunier, T., and E. J. Brook (2001), Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period, *Science*, 291, 109–112.
- Blunier, T., et al. (1998), Asynchrony of Antarctic and Greenland climate change during the last glacial period, *Nature*, 394, 739–743.
- Brook, E. J., S. Harder, J. P. Severinghaus, E. J. Steig, and C. M. Suher (2000), On the origin and timing of rapid changes in atmospheric methane during the last glacial period, *Global Biogeochem. Cycles*, 14, 559–572.
- Caillon, N., J. P. Severinghaus, J. Jouzel, J.-M. Barnola, J. Kang, and V. Y. Lipenkov (2003), Timing of atmospheric CO₂ and Antarctic temperature changes across Termination III, *Science*, 299, 1728–1731.
- Campen, R. K., T. Sowers, and R. B. Alley (2003), Evidence of microbial consortia metabolizing within a low-latitude mountain glacier, *Geology*, 31, 231–234.
- Das, S. (2003), West Antarctic ice sheet surface melting and Holocene variability, Ph.D. thesis, Pa. State Univ., University Park.
- Delmas, R. J. (1993), A natural artifact in Greenland ice-core CO₂ measurement, *Tellus, Ser.*, 45, 391–396.
- Delmas, R. J., J. M. Ascencio, and M. Legrand (1980), Polar ice evidence that atmospheric CO₂ 20,000yr BP was 50% of present, *Nature*, 284, 155–157.
- 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.
- EPICA Dome C 2001–02 science and drilling teams (2002), Extending the ice core record beyond half a million years, *Eos Trans. AGU*, 83(45), 509, 517.
- Etheridge, D. M., and C. W. Wookey (1989), Ice core drilling at a high accumulation area of Law Antarctica, in *Ice Core Drilling: Proceedings of the Third International Workshop on Ice Core Drilling Technology*, edited by C. Rado and D. Beaudoin, pp. 86–96, Cent. Natl. de la Rech. Sci., Grenoble, France.
- Etheridge, D. M., L. P. Steele, R. L. Langenfelds, R. J. Francey, J.-M. Barnola, and V. I. Morgan (1996), Natural and anthropogenic changes in atmospheric CO₂ over the last 1000 years from air in Antarctic ice and firn, *J. Geophys. Res.*, 101, 4115–4128.
- Fischer, H., M. Wahlen, J. Smith, D. Mastroianni, and B. Deck (1999), Ice core records of atmospheric CO₂ around the last three glacial terminations, *Science*, 283, 1712–1714.
- Flückiger, J., E. Monnin, B. Stauffer, J. Schwander, and T. F. Stocker (2002), High-resolution Holocene N₂O ice core record and its relationship with CH₄ and CO₂, *Global Biogeochem. Cycles*, 16(1), 1010, doi:10.1029/2001GB001417.
- Goujon, C., J.-M. Barnola, and C. Ritz (2003), Modeling the densification of polar firn including heat diffusion: Application to close-off characteristics and gas isotopic fractionation for Antarctica and Greenland sites, *J. Geophys. Res.*, 108(D24), 4792, doi:10.1029/2002JD003319.
- Hamilton, G. S. (2002), Mass balance and accumulation rate across Siple Dome, West Antarctica, *Ann. Glaciol.*, 35, 102–106.
- Iglewicz, B., and D. C. Hoaglin (1993), *How to Detect and Handle Outliers*, ASQC Basic Ref. Qual. Control, vol. 16, 87 pp., Am. Soc. for Qual. Control, Milwaukee, Wis.
- Indermühle, A., et al. (1999), Holocene carbon-cycle dynamics based on CO₂ trapped in ice at Taylor Dome, Antarctica, *Nature*, 398, 121–126.
- Indermühle, A., E. Monnin, B. Stauffer, T. F. Stocker, and M. Wahlen (2000), Atmospheric CO₂ concentration from 60–20 kyr BP from the Taylor Dome ice core, Antarctica, *Geophys. Res. Lett.*, 27, 735–738.
- Kawamura, K., T. Nakazawa, S. Aoki, S. Sugawara, Y. Fujii, and O. Watanabe (2003), Atmospheric CO₂ variations over the last three glacial-interglacial climate cycles deduced from the Dome Fuji deep ice core, Antarctica using a wet extraction technique, *Tellus, Ser. B*, 55, 126–137.
- McConnell, J. R. (1997), Investigation of the atmosphere-snow transfer process for hydrogen peroxide, Ph.D. dissertation, Dep. of Hydrol. and Water Resour., Univ. of Ariz., Tucson.
- Monnin, E., A. Indermühle, A. Daellenbach, J. Flückiger, B. Stauffer, T. F. Stocker, D. Raynaud, and J.-M. Barnola (2001), Atmospheric CO₂ concentrations over the last glacial termination, *Science*, 291, 112–114.
- Nefel, A., H. Oeschger, J. Schwander, B. Stauffer, and R. Zumbunn (1982), Ice core sample measurements give atmospheric CO₂ content during the past 40,000 yr, *Nature*, 259, 220–223.
- Nefel, A., H. Oeschger, J. Achvander, and B. Stauffer (1983), Carbon dioxide concentration in bubbles of natural cold ice, *J. Phys. Chem.*, 87, 4116–4120.
- Nefel, A., H. Oeschger, T. Stauffelbach, and B. Stauffer (1988), CO₂ record in the Byrd ice core 50,000–5000 years BP, *Nature*, 331, 609–611.
- Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, 399, 429–436.
- Raynaud, D., J. Jouzel, J. M. Barnola, J. Chappellaz, R. J. Delmas, and C. Lorius (1993), The ice record of greenhouse gases, *Science*, 259, 926–934.
- Schwander, J., J. Jouzel, C. U. Hammer, J.-R. Petit, R. Udisti, and E. Wolff (2001), A tentative chronology for the EPICA Dome Concordia ice core, *Geophys. Res. Lett.*, 28, 4243–4246.
- Severinghaus, J. P., A. Grachev, and M. Battle (2001), Thermal fractionation of air in polar firn by seasonal temperature gradients, *Geochem. Geophys. Geosyst.*, 2, Paper number 2000GC000146.
- Severinghaus, J. P., A. Grachev, B. Luz, and N. Caillon (2003), A method for precise measurement of argon 40/36 and krypton/argon ratios in trapped air in polar ice with applications to past firn thickness and abrupt climate change in Greenland and at Siple Dome, Antarctica, *Geochim. Cosmochim. Acta.*, 67, 325–343.
- Smith, H. J., M. Wahlen, D. Mastroianni, and K. Taylor (1997a), The CO₂ concentration of air trapped in GISP2 ice from the Last Glacial Maximum-Holocene transition, *Geophys. Res. Lett.*, 24, 1–4.
- Smith, H. J., M. Wahlen, D. Mastroianni, K. Taylor, and P. Mayewski (1997b), The CO₂ concentration of air trapped in Greenland Ice Sheet Project 2 ice formed during periods of rapid climate change, *J. Geophys. Res.*, 102, 26,577–26,582.
- Smith, H. J., H. Fischer, M. Wahlen, D. Mastroianni, and B. Deck (1999), Dual modes of the carbon cycle since the last glacial maximum, *Nature*, 400, 248–250.
- Staffelbach, T., B. Stauffer, A. Sigg, and H. Oeschger (1991), CO₂ measurements from polar ice cores: More data from different sites, *Tellus, Ser. B*, 43, 91–96.
- Stauffer, B., A. Nefel, H. Oeschger, and J. Schwander (1985), CO₂ concentration in air extracted from Greenland ice samples, in *Greenland Ice Core: Geophysics, Geochemistry and the Environment*, *Geophys.*

- Monogr. Ser.*, vol. 33, edited by C. C. Langway Jr. et al., pp. 85–89, AGU, Washington, D. C.
- Steig, E. J., D. L. Morse, E. D. Waddington, and P. J. Polissar (1998), Using the sunspot cycle to date ice cores, *Geophys. Res. Lett.*, *25*, 163–166.
- Tabacco, I. E., A. Passerini, F. Corbelli, and M. Gorman (1988), Determination of the surface and bed topography at Dome C, East Antarctica, *J. Glaciol.*, *44*, 185–191.
- Taylor, K. C., et al. (2004a), Dating the Siple Dome, Antarctic ice core by manual and computer interpretation of annual layering, *J. Glaciol.*, in press.
- Taylor, K. C., et al. (2004b), Abrupt climate change around 22 ka on the Siple Coast of Antarctica, *Quat. Sci. Rev.*, *23*, 7–15.
- Tschemi, J., and B. Stauffer (2000), Reconstructing past atmospheric CO₂ concentration based on ice-core analyses: Open questions due to in situ production of CO₂ in the ice, *J. Glaciol.*, *46*, 45–53.
- Waddington, E. D., and D. L. Morse (1994), Spatial variations of local climate at Taylor Dome, Antarctica: Implications for paleoclimate from ice cores, *Ann. Glaciol.*, *20*, 219–225.
- Wahlen, M., D. Allen, B. Deck, and A. Herchenroder (1991), Initial measurement of CO₂ concentrations (1530 to 1940 AD) in air occluded in the GISP2 ice core from central Greenland, *Geophys. Res. Lett.*, *18*, 1457–1460.
-
- J. Ahn, B. L. Deck, and M. Wahlen, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093, USA. (jiahn@ucsd.edu)
- E. J. Brook, Department of Geology and Program in Environmental Science, Washington State University, Vancouver, WA 98686, USA.
- P. A. Mayewski, Climate Change Institute, University of Maine, Orono, ME 04469, USA.
- K. C. Taylor, Desert Research Institute, University of Nevada, Reno, NV 89512, USA.
- J. W. C. White, INSTAAR, University of Colorado, Boulder, CO 80309, USA.