A abrupt change in atmospheric CO2 during the last ice age

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[1] During the last glacial period atmospheric carbon dioxide and temperature in Antarctica varied in a similar fashion on millennial time scales, but previous work indicates that these changes were gradual. In a detailed analysis of one event we now find that approximately half of the CO2 increase that occurred during the 1500-year cold period between Dansgaard-Oeschger (DO) events 8 and 9 happened rapidly, over less than two centuries. This rise in CO2 was synchronous with, or slightly later than, a rapid increase of Antarctic temperature inferred from stable isotopes. Citation: Ahn, J., E. J. Brook, A. Schmittner, and K. Kreutz (2012), Abrupt change in atmospheric CO2 during the last ice age, Geophys. Res. Lett., 39, L18711, doi:10.1029/2012GL053018.

[2] Ancient air preserved in ice cores provides important information about past variations in atmospheric CO2, which can inform understanding of future climate-carbon cycle feedbacks [Friedlingstein et al., 2006]. Previous ice core work for the last glacial period showed that CO2 and Antarctic temperature rose during long, cold stadial periods in the northern hemisphere, and that Antarctic temperature cooled and CO2 slowed or stopped rising when stadials ended with abrupt northern hemisphere warming [e.g., Ahn and Brook, 2008; Bereiter et al., 2012]. Although these observations have been simulated in models forced by freshwater input in the North Atlantic [e.g., Schmittner and Galbraith, 2008], the governing mechanisms for the climate-carbon cycle interactions are not well understood, in part due to insufficient resolution, precision and/or chronology of previously published ice core records.

[3] Details of CO2 analysis at Oregon State University (OSU) are described in Ahn et al. [2009]. We analyzed Siple Dome ice samples from 58 depths from 819–905 m depth (37.1–52.4 ka) and 105 Byrd ice samples from 40 depths from 1685.1–1814.5 m (36.8–42.9 ka). CO2 concentrations are reported on the WMOX2007 CO2 mole fraction scale. We utilized nitrogen isotope data from Brook et al. [2005], Sowers et al. [1992] and Bender et al. [1995] for corrections of 0.8–0.9 and 1.0–1.5 ppm for gravitational fractionation in Siple Dome and Byrd ice, respectively.

[4] CH4 analysis was performed at OSU using methods described by Mitchell et al. [2011]. We analyzed 62 new samples from 40 depths of the Siple Dome core, 87 samples from 48 depths of the Byrd core, 56 samples from 34 depths from the Taylor Dome core, and 88 samples from 44 depths of the GISP2 core. Data are reported on the NOAA04 methane concentration scale [Dlugokencky et al., 2005].

3. Results

[5] Our Siple Dome and Byrd records cover the time period from 37~47 ka, during which Antarctica experienced two major warming events (A1 and A2) and several abrupt warming/cooling (DO) events occurred in Greenland (Figure 1 and Figure S1 in the auxiliary material). To place the records on the same chronology we synchronized the age scales using existing and new methane data, assuming methane concentration variations in Greenland and Antarctica were synchronous [Blunier and Brook, 2001] (Figure 1, and Figure S1 and Table S1 in Text S1). Although measurements of CO2 in Greenland ice cores might provide a more direct way to compare Greenland climate variations with carbon dioxide changes, reconstruction of the CO2 history from Greenland ice cores is difficult due to high levels of impurities in ice [Stauffer, 2006].

[6] We obtained sub-centennial CO2 data for the period from about 40 to 38 ka (Figure 1), corresponding to the Greenland stadial between Dansgaard-Oeschger [DO] events 8 and 9, and the time period of the A1 warming in Antarctica [Blunier and Brook, 2001] or AIM8 (Antarctic Isotope Maximum 8) [EPICA Community Members, 2006]. Heinrich event 4, an abrupt glacial discharge event in the North Atlantic occurred in the time interval and the stadial is referred to Heinrich stadial 4 [Skinner and Elderfield, 2007]. In general, CO2 strongly covaries with the Antarctic stable isotope records on centennial time scales over this period. After the DO9 warming event in Greenland, both CO2 and δ18Oice in the Byrd and Siple Dome records started to increase at ~40.0 ka. The initial CO2 rise was somewhat gradual, but at 39.6 ka a 10 ppb jump occurred over ~150 years in both Siple and Byrd records. Following that jump CO2 levels show two oscillations of smaller amplitude (5 ppm) before an additional abrupt increase at ~38.3 ka, synchronous with DO-8 warming in Greenland. After the abrupt DO8 warming in Greenland, CO2 remained high for 700–800 years while Antarctica cooled as shown in both the Byrd and Siple Dome records, confirming the decoupling of CO2 and Antarctic temperature proxies following Antarctic
warming observed in previous Byrd ice core results [Ahn and Brook, 2008]. We note that the CO$_2$ in Byrd is uniformly 3–7 ppm higher than in Siple Dome for the studied age interval (Figure S2 in Text S1), which we believe is probably related to the long duration of storage for the Byrd core (drilled in 1968), but the timing and patterns of CO$_2$ change are similar. High resolution Ca$^{2+}$ and non-sea-salt Ca (nssCa$^{2+}$) concentration records from the Siple Dome ice core [Mayewski et al., 2009] do not show any significant correlation with the abrupt CO$_2$ rise (Figure S3 in Text S1), indicating that the abrupt CO$_2$ rise is not likely produced by carbonate-acid reaction in the ice. Similar data are not available for Byrd. Although the abrupt changes in our data are defined by only a few data points, they are reproducible in the two ice cores, and we further note that each plotted point is the mean of several replicate samples. The replicate Byrd ice samples were generally analyzed on different days over 6 months.

4. Abrupt Rise of CO$_2$ During Heinrich Stadial 4

[7] We call attention to the abrupt change in CO$_2$ of ~10 ppm at ~39.6 ka. The Siple Dome record shows the rise interrupted by a rapid initial drop of ~9 ppm, but this is not confirmed in the Byrd ice core. If this event were real, we would expect both cores show the initial drop of CO$_2$. Thus we disregard this data point in the Siple Dome record for a conservative calculation of the rate of CO$_2$ increase (Figure 1 and Figures S1, S2, and S4 in Text S1). In Siple Dome 60% of the 10 ppm increase occurred over at most ~70 years (9 ppm/century). In Byrd, an ~8 ppm increase is observed over 50 years (~15 ppm/century). Considering the data resolution and the smoothing of the gas record by diffusion in the firm [Brook et al., 2005] and ice matrix [Ahn et al., 2008], the actual atmospheric CO$_2$ change could have been faster. The exact rate of the abrupt CO$_2$ change is difficult to estimate but it is likely that the entire change took place in less than two centuries.

[8] The 10 ppm increase is about half the amplitude of the multi-millennial variations associated with the major Antarctic warm events and indicates that atmospheric CO$_2$ can change more rapidly than suggested by previous lower-resolution ice core records for the last glacial period. Previous high-resolution, but highly scattered and lower precision Byrd CO$_2$ measurements from the University of Bern [Stauffer et al., 1998] also showed abrupt CO$_2$ change at the same depth as we observed (Figure S5b in Text S1). In addition, Taylor Dome ice core records [Indermühle et al., 2000] also show a rapid rise of CO$_2$ with a lower resolution at similar ages (on our improved chronology with better CH$_4$ correlation, Figure S5d in Text S1). EDML ice core records also show a similar two step abrupt rise in CO$_2$ at A1, with lower resolution [Lüthi et al., 2010].

[9] The abrupt rise of CO$_2$ at ~39.6 ka is synchronous with or slightly later than a rapid rise of temperature proxies ($\delta^{18}$O, $\delta$D) in the Byrd and Siple Dome records within the uncertainty of ice age- gas age difference of 150–200 years [Blunier and Brook, 2001; Brook et al., 2005]. The rapid warming occurred ~400 yrs after the start of A1 warming in both Siple Dome and Byrd ice cores (Figures 1 and 2). Rapid warming at a similar time interval is also observed in EDML [EPICA Community Members, 2006] and Dome C [Jouzel et al., 2007] ice core records (Figure 2 and Figures S6f–S6i in Text S1). Similar features may be present in Vostok [Petit et al., 1999] and Dome Fuji [Watanabe et al., 2003] records, but are difficult to interpret due to low time resolution and/or chronological uncertainty. The abrupt CO$_2$ rise is also
synchronous with a small step-like increase of CH$_4$ at $\sim$39.6 ka in the high resolution Byrd and Siple Dome CH$_4$ records (Figure 1). The synchronicity of these events is firmly established because the CO$_2$ and CH$_4$ increases occurred at the same depth in the same ice cores, circumventing uncertainty in the ice age–gas age difference (Figures 1 and 2 and Figure S5 in Text S1). The Byrd and Siple Dome ice cores also show that the step-like increase of CH$_4$ starts with a short CH$_4$ peak.

[10] Our new high-precision data from GISP2 ice core also show a step in CH$_4$ during Heinrich stadial 4, synchronous with a small oscillation of $\delta^{18}$O$_{ice}$ within the relative age uncertainty between ice and gas ages (Figure S5 in Text S1), indicating that abrupt CO$_2$ rise at $\sim$39.6 ka might have been synchronous with this small Greenland warming. However, we point out that the small rise of $\delta^{18}$O in GISP2 records is not clearly apparent in other Greenland ice cores [Blunier and Brook, 2001; EPICA Community Members, 2006]. Nonetheless, the CH$_4$ change itself indicates that a climate event occurred during the abrupt CO$_2$ increase.

5. Possible Mechanisms and Discussion

[11] To explore possible governing mechanisms for the abrupt CO$_2$ changes, we first compared our CO$_2$ data with nssCa$^{2+}$ and ssNa$^+$ (sea-salt-Na$^+$) flux records from Antarctic ice cores [Mayewski et al., 2009; Fischer et al., 2007]. Those records were used as proxies for Patagonian dust source strength and sea ice extent in the Southern Ocean, respectively, in previous studies for Dome C and EDML ice cores (Figure 2) [Fischer et al., 2007]. Both have been suggested as potential controls on atmospheric CO$_2$ [Fischer et al., 2007]. The Siple Dome, Dome C and EDML ice cores show that nssCa$^{2+}$ flux is anti-correlated with the isotopic record (Figure 2), suggesting that Patagonian (or other continental) dust source strength (nssCa$^{2+}$ flux) started to decrease $\sim$400 years before the abrupt CO$_2$ rise at 39.6 ka. The gradual CO$_2$ rise starting at $\sim$40.0 ka is inversely correlated with nssCa$^{2+}$ and therefore presumably with reduced iron input in the Southern Ocean [Mayewski et al., 2009; Fischer et al., 2007], which could result in an increase in atmospheric CO$_2$ due to reduced iron-fertilization [Fischer et al., 2007], but we do not observe an abrupt change in nssCa$^{2+}$ at 39.6 ka. In contrast, ssNa$^+$ flux records from the three Antarctic ice cores are not consistent (Figure 2). The EPICA EDML ice core shows a rapid drop of ssNa$^+$ flux $\sim$400 years after the onset of A1 warming, synchronous with the abrupt CO$_2$ rise we observed in the Siple and Byrd ice cores, indicating that the abrupt CO$_2$ rise might be related to increase of CO$_2$ outgassing from areas in the Southern Ocean, which had been blocked by sea ice [Stephens and Keeling, 2000]. However, the relationship between abrupt CO$_2$ change and ssNa$^+$ flux is not clear in the Siple Dome and Dome C records. The differences in ssNa$^+$ flux records among the three cores could be due to difference in sea salt aerosol source regions (EDML from Atlantic sector, Dome C from Indian sector and Siple Dome from Pacific sector) and/or different sensitivity in the source areas and/or different degree of deposition and remobilization during transportation from the source regions [Fischer et al., 2007].

[12] Oceanic meridional overturning circulation is another potential control on atmospheric CO$_2$ [Marchal et al., 1998; Menviel et al., 2008; Schmittner et al., 2007]. To examine this we compared our data with Atlantic sediment records that indicate that Antarctic Bottom Water was strengthened and possibly Atlantic meridional overturning circulation (AMOC) was reduced during the Heinrich stadial 4 [Shackleton et al., 2000] (Figure 1b). Similar changes are well simulated in carbon cycle models for millennial variations during the last glacial period. Such models start from weakening of the North Atlantic Deep Water (NADW) formation by fresh water forcing in the North Atlantic [Marchal et al., 1998; Menviel et al., 2008; Schmittner et al., 2007] and predict that several different mechanisms for atmospheric CO$_2$ change are important, including increase in sea surface temperature in the Southern Ocean [Marchal et al., 1998], reduced stratification in the Southern ocean [Schmittner et al., 2007] and increased preformed nutrients in the global ocean [Schmittner and Galbraith, 2008]. Reduced AMOC due to freshwater forcing also affects terrestrial vegetation and carbon cycling in models, but the sign of CO$_2$ change is model dependent [Köhler et al., 2005; Menviel et al., 2008]. None of the models used to examine CO$_2$ variations in response to circulation shut down predict the abrupt features of CO$_2$ changes reported here. However, some marine proxies show sharp changes in the deep water off the Iberian Margin [Skinner and Elderfield, 2007; Margari et al., 2010], sea surface temperature in the subtropical North Atlantic [Sachs and Lehman, 1999] and upwelling in the Southern Ocean [Anderson et al., 2009] in...
that data resolution and replication, and the exact timing relative to the abrupt CO2 changes is not well constrained.

[13] Change in atmospheric circulation could also be involved in abrupt changes in CO2. Changes in westerly wind stress strength and position in the Southern Ocean, perhaps driven by cooling in the high latitude northern hemisphere, might affect upwelling of CO2-rich deep water, therefore CO2 outgassing, as suggested for glacial-interglacial [Toggweiler et al., 2006] and millennial [Anderson et al., 2009; Lee et al., 2011] CO2 variations. Speleothem δ18O records from Hulu cave in China [Wang et al., 2001] and Pacupauain Cave in the central Peruvian Andes [Kanner et al., 2012] show increase in East Asian Summer Monsoon (EASM) and decrease in South American Summer Monsoon (SASM) strength, respectively, which are synchronous with Greenland DO events (Figure 1j). During Heinrich stadial 4, the speleothem δ18O records show a peak (depletion in Hulu cave δ18O and enrichment in Pacupauain cave δ18O), which indicates enhanced (reduced) EASM (SASM) activity and shares the trend of CO2 variation at the same time interval. The speleothem δ18O change appears to occur slightly later than that of CO2 in our age scales for Siple Dome and Byrd (Figure 1j). However, given uncertainties in the ice core and speleothem chronology it seems likely that the speleothem δ18O peak is actually synchronous with the small CH4 peak after DO 9 and therefore also the abrupt CO2 increase at 39.6 ka and the small warming in the GISP2 record at this time (Figures 1b and 1e and Figures S1b, S1d, and S5a–S5c in Text S1). Perhaps climate changes associated with an enhanced (reduced) precipitation in northern (southern) hemisphere affected terrestrial carbon and atmospheric CO2. The speleothem δ18O reversal after the peak indicates a reduced EASM and enhanced SASM activity and southward shift of ITCZ (Intertropical Convergence Zone). If those events are associated with the abrupt glacial discharge in the North Atlantic during Heinrich event 4 (H4) [Kanner et al., 2012], it is unlikely that H4 predates the abrupt CO2 rise (Figure 1).

[14] Although the ocean is often called on to explain past changes in CO2, some model studies suggest that abrupt CO2 changes could be due to changes in the terrestrial carbon cycle [Gerber et al., 2003; Köhler et al., 2010]. To demonstrate that the terrestrial carbon cycle could change CO2 quickly we use the UVic (University of Victoria) coupled climate-carbon cycle model (version 2.8) with a glacial-carbon cycle model (version 2.8) with a glacial

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