Siple Dome ice reveals two modes of millennial CO$_2$ change during the last ice age

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Reconstruction of atmospheric CO$_2$ during times of past abrupt climate change may help us better understand climate-carbon cycle feedbacks. Previous ice core studies reveal simultaneous increases in atmospheric CO$_2$ and Antarctic temperature during times when Greenland and the northern hemisphere experienced very long, cold stadial conditions during the last ice age. Whether this relationship extends to all of the numerous stadial events in the Greenland ice core record has not been clear. Here we present a high-resolution record of atmospheric CO$_2$ from the Siple Dome ice core, Antarctica for part of the last ice age. We find that CO$_2$ does not significantly change during the short Greenlandic stadial events, implying that the climate system perturbation that produced the short stadials was not strong enough to substantially alter the carbon cycle.
Ice core records from Greenland reveal a detailed history of abrupt climate change during the last glacial period. Warm and cold periods (interstadial and stadial, respectively) repeated on millennial timescales but rapid switches between the two happened in decades\textsuperscript{1,2}. Antarctic ice core records, however, reveal gradual warming during Greenlandic stadials and cooling during interstadials\textsuperscript{3,4}. The out-of-phase interhemispheric climate relationship is usually referred to as the ‘bipolar seesaw’\textsuperscript{7} and the most popular hypothesis for the control mechanism includes reorganization of ocean-atmosphere circulation and change in meridional heat transport, possibly caused by fresh water input into the North Atlantic\textsuperscript{8–10}.

Reconstruction of atmospheric CO\textsubscript{2} during abrupt climate change events may help us better understand climate-carbon cycle feedbacks and provide data for testing carbon cycle models under variety of boundary conditions. Existing Antarctic ice core records show CO\textsubscript{2} increases during long Greenlandic stadials, which are also accompanied by major Antarctic warmings\textsuperscript{11,12}. Ventilation of CO\textsubscript{2}-rich deep water in the Southern Ocean may have controlled ocean-atmosphere carbon exchange and therefore atmospheric CO\textsubscript{2} concentration\textsuperscript{13}. Marine sediment records from the Southern Ocean indicate increased opal flux\textsuperscript{14} and reduced stratification\textsuperscript{13} during the Younger Dryas event and the long stadial preceding the Bolling-Allerød event\textsuperscript{14,15}, both times of rising CO\textsubscript{2}, and can be interpreted as a record of increased upwelling and CO\textsubscript{2} outgassing in the Southern Ocean\textsuperscript{14,15}. During the same time intervals, the Atlantic meridional overturning circulation (AMOC) was reduced and the Antarctic temperature gradually increased\textsuperscript{16,17}. During the long stadials of the last ice age, marine sediment records indicate shoaled AMOC\textsuperscript{18} and increased opal flux\textsuperscript{14} in the Southern Ocean, although the chronology of the proxy for the latter is not well constrained. The shoaling of AMOC likely coincided with reduction in AMOC strength that might have caused reduction in northward oceanic heat transport, the gradual warming in Antarctica and CO\textsubscript{2} outgassing from the Southern ocean during the long stadials\textsuperscript{16,14}, analogous to the early stage of the last deglaciation. Antarctic warming and CO\textsubscript{2} increase\textsuperscript{18,19,20}.

High-resolution records from the EPICA Dronning Maud Land (EDML) ice core in east Antarctica show the ‘bipolar seesaw’ operated not only during the major long stadials but also during other short ones, and that stadial duration is positively correlated with the magnitude of the temperature increase in Antarctica. These observations support the hypothesis of reduction in AMOC during both long and short stadials\textsuperscript{21}, although there is no clear marine evidence of AMOC reduction during each of the short stadials, perhaps owing to insufficient data resolution and/or chronology\textsuperscript{22}.

By analogy to the relationship between CO\textsubscript{2} and major Antarctic warmings/long Greenlandic stadials, we might expect small CO\textsubscript{2} increases during the small Antarctic warmings/short Greenlandic stadials. However, atmospheric CO\textsubscript{2} change during the short stadials is not well resolved in existing ice core records owing to low temporal data resolution (280–570 years\textsuperscript{11,12,22}).

We investigate CO\textsubscript{2} variations during the short Greenlandic stadials, with a multi-decadal to centennial CO\textsubscript{2} record with a mean sampling resolution of 95 years, from the Siple Dome ice core, Antarctica. Our new results cover the time interval of

**Figure 1 | High-resolution CO\textsubscript{2} and climate records during abrupt climate change during the last ice age.** (a) Greenlandic isotopic temperature record from the NGRIP ice core\textsuperscript{17}. Black numbers represent Dansgaard-Oeschger events. HS stands for Heinrich stadial, indicating long stadials that include Heinrich events. (b) Atmospheric CH\textsubscript{4} records from Greenland (grey)\textsuperscript{23}, Siple Dome (red)\textsuperscript{24} and EDML (blue)\textsuperscript{21} ice cores. Black dots are new Siple Dome CH\textsubscript{4} data (this study). Red triangles indicate age control points. (c) Atmospheric CO\textsubscript{2} record from Siple Dome, Antarctica ice core (this study). Red line represents 300-year running means of the CO\textsubscript{2} record. Black dots are published records\textsuperscript{23}. (d) Antarctic temperature proxy records from Siple Dome (dark blue)\textsuperscript{24} and EDML (grey)\textsuperscript{23} ice cores. All the ages are synchronized on Greenland Ice Core Chronology 2005 (GICC05) timescale. Blue and pink boxes indicate time intervals of short and long stadials (Greenlandic cold spans), respectively. During those stadials, Antarctic temperature increased.
Greenlandic abrupt climate events (Dansgaard-Oeschger or DO events) DO2–7 and our sampling resolution is sufficient to examine CO2 trends during the short stadials lasting for 800–1200 years. Combined with recently published high-resolution data for DO8–10 from the same core23, we constructed a complete high-resolution CO2 record from 22 to 41 ka.

**Results**

**Natural smoothing of gas records in the Siple Dome ice core.** Snow accumulation rates at the Siple Dome are relatively high, and therefore smoothing of gas records by diffusion and gradual bubble close-off in the firm (unconsolidated snow layer on the top of ice sheet) is relatively small24. The high snow accumulation rates also result in a small uncertainty in the relative timing between gas ages and ice ages (Δage)25, allowing better comparison of gas records with temperature proxy records24. A firm densification model for Siple Dome shows Δage of 500–1000 years during the 22–41-ka period24. Because the width of the gas age distribution at half-height is typically about 10% of Δage25–28, we estimate the gas age distribution of the Siple Dome record to be <100 years during the time interval of study. The sharp increases in the Siple Dome CH4 record (Fig. 1) clearly confirm that the smoothing of gas records is minimal on multi-centennial timescales and supports our estimation of smoothing of the Siple Dome CO2 record.

**Two modes of CO2 change during Greenlandic stadials.** As shown in Fig. 1, we observe small CO2 variations of ~5 p.p.m. on centennial timescales during the short stadials. A 300-year running mean (red curve) removes these features (Fig. 1), illustrating that CO2 change was negligible on multi-centennial timescales. We observe small decreases on longer timescales during most of the short stadials (Fig. 1), but these are part of a long-term trend. After detrending it becomes clear that the CO2 change associated with short stadials themselves is insignificant (Fig. 2a). In contrast, we observe CO2 increases during the long stadials, confirming previous results from different Antarctic ice cores11,12,22,25 (Fig. 2a). The isotopic temperature proxy (δDice) from the Siple Dome ice core shows small Antarctic warmings during most of the short stadials (Fig. 2b) and confirms previous results from the EDML ice core21, implying that the small Antarctic warmings during the short stadials are not only local features but at least of larger regional extent because Siple Dome is located in the Pacific sector, while the EDML core is in the Atlantic sector in Antarctica. Combining the Siple Dome CO2 and climate records, we plot the time evolution of CO2 versus the temperature proxy (δDice) anomalies during Greenlandic stadials or Antarctic warmings, using the detrended Siple Dome CO2 and temperature proxy records for short stadials (Fig. 2c). We find that CO2 and δDice anomalies are not significantly correlated during the short stadials (average r = 0.0), but positively correlated during the long stadials (average r = 0.84) (Fig. 2c). A slight temperature decrease in the Siple Dome δDice between DO9 and 10 is not confirmed in the EDML isotopic temperature (δDice) record21 and excluded in our calculation. We note that Siple Dome isotopic temperature (δDice) between DO3 and 4 increases, but at EDML it decreases, presumably owing to local effects. Our finding of the two different modes of CO2 change during Greenlandic stadials for the period 22–41 ka is consistent with the results of a recent, lower resolution study of CO2 variations from 38 to 115 ka12, which shows <5 p.p.b. variations in CO2 during the short stadial events of marine isotope stage 3.

**Discussion**

The small-to-insignificant CO2 change during the short stadials may imply that AMOC perturbations happened at these events
but were too short to result in a change in atmospheric CO₂. If this were the case, we would expect to observe no CO₂ increase during the first 800–1200 years of the short stadials, because duration of the short stadials ranges 800–1200 years. However, we observe that CO₂ increases from the beginning of the long Greenlandic stadials predating DO8 and DO4 (Fig. 2a). The time lag of CO₂ relative to the isotopic signal during Greenlandic stadials predating DO12 and 17 from other ice core records appears small as well11,12. However, we cannot clearly rule out the possibility of a time lag of several centuries (Fig. 3). In addition, there is some ambiguity about the start of the long stadial predating DO4, which is conventionally defined by the end of a small temperature proxy peak (DO4.1)21. We follow convention here, but note that additional high-resolution data from other long stadial events will be needed to further address the question of when CO₂ starts to rise during events of this type. The above observation suggests that climate perturbations associated with the long and short stadials are different. Cave deposits reveal less weakening in the Asian monsoon30 and less intense South American monsoon31 during the short stadials compared with the long stadials, suggesting that the perturbation to the climate system related to the short stadial events in Greenland was weaker than for the long ones. A comparison of Antarctic ice core climate records with a thermodynamic model also indicates that the long stadials were caused by a stronger climate perturbation than short ones32. Finally, although it is not conclusive, δ¹³C in benthic foraminifera from North Atlantic sediment cores indicates less shoaling of AMOC during short stadials than that during the long stadials33. Thus it is likely that strength of the climate perturbation is related to change in atmospheric CO₂ during the Greenlandic stadials. Massive iceberg discharge events in the North Atlantic (Heinrich events) occurred within time intervals of the long stadials. The Heinrich events could have increased fresh water forcing into the North Atlantic and also caused large perturbations to atmospheric circulation (for example, southward movement of the ITCZ 34). However, multiple studies suggest that the Heinrich events lag onsets of long stadials35,36, although exact timing of those events within the stadials is not well constrained37,38.
The control mechanisms for the two CO₂ modes may exist in oceanic processes such as AMOC reduction and consequent upwelling in the Southern Ocean. Those oceanic processes can be linked by change in vertical salinity transport and stratification in the Southern Ocean39 and/or latitudinal shift of Southern Hemisphere Westerlies14,40 and/or strength of the Southern Hemisphere Westerlies1–4. Although we cannot pinpoint a precise oceanic mechanism, we speculate that the weakening in AMOC during the short stadials might have not been sufficient to cause enough of a change in upwelling to impact atmospheric CO₂. Marine proxy data for upwelling in the Southern Ocean do not clearly show strong peaks in between long stadials that bracket several short stadials11, supporting this hypothesis.

Other potential oceanic mechanisms that change CO₂ outgassing include variations in sea ice extent and changes in iron fertilization in the Southern Ocean41,42. Sea-salt-Ne may be a proxy for sea ice extent, but Siple Dome, Dome C and EDML ice core records do not show significant differences between long and short Greenlandic stadials44,45. Proxy records for the Fe-flux (non-sea-salt Ca) from Dome C and EDML cores show highly reduced Fe-flux during several long Greenlandic stadials that predate DO8, but after DO8 the reduction during long stadials is not larger than that during short stadials44. Thus a difference in iron fertilization in the Southern Ocean is not likely the main cause of the two modes in CO₂ change.

Atmospheric CO₂ can be also controlled by exchange of land carbon. Terrestrial carbon is mostly affected by temperature and precipitation because they both control vegetation and organic carbon in soil. Compared with interstadials, paleoxygen data for both short and long stadials indicate colder and dryer conditions in the northern hemisphere, and warmer and wetter conditions in the southern hemisphere, although the magnitude of those changes depends on the type of stadials6. However, model simulations predict either a decrease46,47 or increase48 in land carbon during the stadials. Although we cannot rule out terrestrial control on the two modes of CO₂ change, we suggest that the control mechanism exists more likely in the ocean rather than on land, because we have supporting evidence for an oceanic CO₂ source during the long stadials in the last deglaciation14,15,49,50.

In principle, the lack of change in atmospheric CO₂ could also result from compensating changes in sources (for example, coincident terrestrial uptake and oceanic release) as predicted in models of AMOC shutdown and carbon cycle response46,47,51. However, the global impact of short stadials on the terrestrial biosphere was probably small, given that paleoxygen proxies indicate weaker terrestrial climate perturbations during the short Greenlandic stadials compared with the long ones30,31 as discussed above. Thus, terrestrial uptake balancing oceanic release during the short Greenlandic stadials is not likely the main explanation for the lack of CO₂ response.

Our new high-resolution record defines two modes of millennial scale CO₂ change during stadial events in the northern hemisphere that depend on the nature of the Greenlandic stadial. During short Greenlandic stadials, those not associated with Heinrich events, it is likely that the impact on ocean circulation was not sufficient to release CO₂ from deep ocean to the atmosphere. The lack of correlation between CO₂ and Antarctic temperature change during the short stadials implies that links between Antarctic climate change and high-latitude northern hemisphere climate may have been controlled by shallow oceanic and/or atmospheric processes, while CO₂ change was controlled by deep oceanic and Southern Ocean processes.

Methods
CO₂ concentration measurement. For CO₂ analysis at the Oregon State University, samples were placed in a double-walled stainless steel chamber at – 35 °C, cooled using cold ethanol circulation between the walls, evacuated for 15 min and then crushed with steel pins. Air liberated from the ice was dried in a cold stainless steel coil at – 85 °C and then trapped in ~6 cm² stainless steel sample tubes at – 262 °C. After warming the trapped air to room temperature, the CO₂ mixing ratio was measured with an Agilent 6890N Gas Chromatograph (GC) with a flame ionization detector, with nickel catalyst conversion of CO₂ to CH₄ (mole fraction scale). Daily corrections for the dry extraction and GC analysis were done using several standard airs (197.54 p.p.m.) that were introduced over the ice samples and trapped in sample tubes mimicking the procedure of the air samples from ice. We compared the 2–5 replicates from the same depth. Details of the methods are described in ref. 52. The s.e. for replicates from the same depth averaged 0.6 p.p.m. for the Siple Dome ice. The excellent agreement among the replicates were achieved by careful trimming of the ice surface and improved analytical techniques53 since our early analysis for the same core a decade ago at Scripps Institution of Oceanography54.

CH₄ concentration measurement. CH₄ analysis was separately performed at the Oregon State University15. Duplicate samples with a weight of ~60 g for each were analyzed for each depth interval. Samples were placed in cold glass flask baths in an ethanol bath at – 64.5 °C. The flasks with the ice samples were evacuated for 1 h. The flasks valves were closed and then the ice was melted in a warm water bath. After melting, the flasks were submerged in the cold ethanol bath to refreeze the ice melt. Air liberated from each ice sample was analysed four times with an Agilent 6890N GC with a flame ionization detector. Data are reported on the NOAA4 methane concentration scale.

Synchronization of ice core records. Our CO₂ record from the Siple Dome core is synchronized with NGRIP (North Greenland Ice Core Project) ice ages on the Greenland Ice Core Chronology 2005 (GICC05) timescale55 using abrupt CH₄ changes that are near synchronous with abrupt Greenlandic climate change56. We used updated CH₄ records to make better synchronization. The CH₄ data resolution is 82 and 232 years for 23.5–42.3 and 42.3–46.9 k.a., respectively. The GICC05 timescale is based on layer counting of Greenland ice cores and agrees well with other absolute ages such as cave deposit records55. At DO2, the correlation between CH₄ increase and Greenlandic warming is not clear, and thus we correlate Siple Dome CH₄ with the NGRIP CH₄ record. The age tie points are listed in Table 1. Their uncertainty is controlled primarily by the CH₄ data resolution. The age differences were linearly interpolated at depths between the tie points, and we reconstructed new ages at those depths by adding the calculated difference to the original ages14. Synchronized ice ages were determined using published estimates of ice age–gas age difference57.

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