Atmospheric CO₂ and Climate on Millennial Time Scales During the Last Glacial Period

Jinho Ahn* and Edward J. Brook

Reconstructions of ancient atmospheric carbon dioxide (CO₂) variations help us better understand how the global carbon cycle and climate are linked. We compared CO₂ variations on millennial time scales between 20,000 and 90,000 years ago with an Antarctic temperature proxy and records of abrupt climate change in the Northern Hemisphere. CO₂ concentration and Antarctic temperature were positively correlated over millennial-scale climate cycles, implying a strong connection to Southern Ocean processes. Evidence from marine sediment proxies indicates that CO₂ concentration rose most rapidly when North Atlantic Deep Water shoaled and stratification in the Southern Ocean was reduced. These increases in CO₂ concentration occurred during stadial (cold) periods in the Northern Hemisphere, several thousand years before abrupt warming events in Greenland.

The last glacial period was characterized by abrupt climate and environmental changes on millennial time scales. Prominent examples include abrupt warming and cooling in Greenland ice core records (Dansgaard-Oeschger, or DO, events) (1, 2) and abrupt iceberg discharges in the North Atlantic (Heinrich, or H, events) (3), the latter appearing to predate the longest and largest DO events (Fig. 1A). Age synchronization between Greenland and Antarctic ice cores through atmospheric CH₄ variations reveals that Antarctic and Greenlandic temperature are linked, but not in phase (4, 5) (Fig. 1, A, B, and D). Antarctic warming started before warming in Greenland for most of the large millennial events in the records, and Antarctic temperatures began to decline when Greenland rapidly warmed. Model and ice core studies suggest that this link is maintained by changes in meridional overturning circulation (6, 7).

In contrast to the interhemispheric climate link, the relation between atmospheric CO₂ and climate, in the glacial period (~20 to 120 thousand years ago), has not been as well documented because of scatter in data sets (8) and/or chronological uncertainties (9). Understanding CO₂ variability is important, however, because of the direct role of CO₂ as a greenhouse gas and the probable influence of changes in ocean circulation on past atmospheric CO₂ concentrations. Here, we provide high-resolution atmospheric CO₂ data from the Byrd ice core (10), with a chronology well synchronized with the Greenland ice cores via CH₄ correlation (4). The data cover the period of 20 to 90 ka (Fig. 1C), including previously published results for 47 to 65 ka (11). We also measured CH₄ in 36 samples from Byrd to better constrain the chronology of the 67- to 87-ka time period [the time of DO-19, 20, and 21 and Antarctic events A5 to A7 (4)] (Fig. 1D). Rapid increases in CH₄ concentration are essentially synchronous with abrupt warming in Greenland within decades (12–14). With CH₄ and CO₂ data from the same core, and in many cases from the same samples, we could directly study the phasing between CO₂ and Greenland temperature variations, circumventing uncertainties due to age differences between ice and gas in ice core records (12–14).

We call attention to two distinct features of atmospheric CO₂ variations associated with climate changes in the Northern and Southern Hemispheres. First, CO₂ variation is strongly correlated with δ¹⁸Oice in the Byrd core, a proxy for site temperature, but whereas CO₂ remained relatively stable for about 1 to 2 ka after reaching maximum levels associated with peaks in Antarctic warming, Antarctic temperature dropped rapidly (Fig. 1, B and C, and fig. S1). In contrast to the slow decline of CO₂ relative to Antarctic cooling, the onsets of CO₂ increases are generally synchronous with Antarctic warming within data and age uncertainties (fig. S1).

Second, an increase in CO₂ precedes, by 2 to 5 ka, the abrupt warming in Greenland associated with DO events, 8, 12, 14, 17, 20 and 21, the largest and longest abrupt events in the Greenland record over this time period (Figs. 1, A and C, and 2) (DO-19 may be an exception, but the timing of the onset of CO₂ rise is difficult to determine). The CO₂ increase slowed just after the abrupt warming of those events. We do not resolve any similar CO₂ variability associated with the shorter DO climate oscillations in the 37– to 65-ka period (DO-9, 11, 13, 15) with the current data set, but small variations associated with the shorter DO cycles cannot be excluded. Between 19 and 37 ka, there are some variations that may be associated with DO events 2 to 7, particularly a CO₂ peak at ~28 ka, which may be related to DO-4 and the stadial period preceding it. Higher-resolution data will be needed to further understand this variability.

Models of millennial-scale CO₂ variations suggest that changes in North Atlantic Deep

References and Notes
15. Materials and methods are available as supporting material on Science Online.
18. Y. Maniwa et al., Nat. Mater. 6, 335 (2007).
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Supporting Online Material
www.sciencemag.org/cgi/content/full/322/5898/80/DC1
Figs. S1 and S2

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Atmospheric CO₂ composition and climate during the last glacial period. (A) Greenlandic temperature proxy, δ¹⁸O, (2). Red numbers denote DO events. (B) Byrd Station, Antarctica temperature proxy, δ¹³C O (4). A1 to A7, Antarctic warming events (4). (C) Atmospheric CO₂ concentrations. Red dots [this study and early results for 47 to 65 kya (11) at Oregon State University] and green circles (8) [results from University of Bern] are from Byrd ice cores. Red dots are averages of replicates, and red open circles at ~73 and 76 kya are single data [this study and (11)]. The chronology used for Byrd CO₂ is described in (10). Blue line is from Taylor Dome ice core (9) on the GISP2 time scale (12). Purple line is from EPICA Dome C (27). (D) CH₄ concentrations from Greenland (green) (4) and Byrd ice cores (brown) ([4] and this study). Black dots, new measurements for this study. Vertical blue bars, timing of Heinrich events (H3 to H6) (25, 26). Brown dotted lines, abrupt warming in Greenland.

Water (NADW) formation can affect atmospheric CO₂ concentration through both physical and biological processes in the ocean and terrestrial biosphere. Comparing model results is difficult because of differences in boundary conditions, amount and duration of freshwater forcing, and treatment of the terrestrial biosphere and other relevant processes. Model results suggest that several different mechanisms may relate changes in NADW to changes in atmospheric CO₂ concentration, including increases in Southern Ocean sea surface temperatures and decreased salinity in the North Atlantic (15), and reduced Southern Ocean stratification and release of CO₂ (16). Climate-induced changes in the terrestrial biosphere caused by changes in ocean circulation may also affect the atmospheric CO₂ (17, 18), but the magnitude of this effect is not yet clear.

To explore the possible link between ocean circulation and CO₂, we compared our data with the benthic foraminiferal δ¹³C from Iberian margin sediments at depth of 3146 m, using δ¹³C as a proxy for the balance between northern source and southern source deep waters at this site (19) (Fig. 3C). We also used bulk sediment δ¹⁸O from the Chile margin in intermediate depths as a proxy for input of the Subantarctic Mode Water to this region (20). Following (20), we interpreted this proxy as an indicator of the reduction of stratification in the Southern Ocean (Fig. 3D), which may result from changes in NADW. The two data sets are inversely correlated (note the reverse scale of the δ¹³C) in most time intervals, implying that shoaling NADW is linked to reduction of stratification in the Southern Ocean. The rate of change of CO₂ concentration peaks when these proxies indicate a maximum in NADW shoaling and reduction of stratification in the Southern Ocean (Fig. 3, B to D), implying CO₂ release to the atmosphere during maxima in Southern Ocean destratification, as suggested in model experiments (16). At around 19 to 37 kya, the correlations among the two marine proxies and the rate of change of CO₂ are not as clear as they are in the 37- to 91-ka time period. Other, perhaps longer-term processes may have controlled atmospheric CO₂ during this time period. Alternatively, the geochemical proxies plotted in Fig. 3 may not directly reflect millennial change in ocean circulation as climate approached the last glacial maximum.

Models of long-term glacial-interglacial CO₂ variations indicate that destratification in the Southern Ocean should cause CO₂ to increase (21, 22), although it is not clear if these model results are directly applicable to millennial-scale variations. Other mechanisms that may contribute to glacial-interglacial cycles and may be important on millennial time scales include changes in CO₂ outgassing due to variations in sea ice extent (23) and changes in iron fertilization (24) in the Southern Ocean.

Heinrich events are associated with the cold periods before major DO events, and one scenario that could explain CO₂ variations is that large freshwater fluxes associated with Heinrich events cause changes in ocean circulation and release of CO₂ to the atmosphere through mechanisms discussed above (15, 16). However, based on existing age constraints (3, 25, 26), H events 3, 4, 5, 5a, and 6 appear to have occurred 0 to 3 kya after CO₂ started to rise (Fig. 1 and fig. S2). Unfortunately, precise comparison of CO₂ and all of the H events is prevented by chronological uncertainties. In some cases the relative timing of H events and events in the ice core record can be constrained via correlations between temperature proxies in marine records and ice core data, and identification of ash layers (3, 25, 26). For example, the abrupt warming at DO-15 (defined by the rapid rise in CH₄ concentration, fig. S2) has a correlative feature in North Atlantic sediment records (26) and occurred before H5a, whereas the CO₂ rise associated with A3 started during or before DO-15, and therefore also before H-5a. However, for other H events, the timing of the associated CO₂ rise cannot be precisely determined in this way given the current time resolution of the ice core records.

The data also indicate abrupt increases in CO₂ concentration of ~10 parts per million (ppm) at the times of abrupt warming associated with DO-19, 20, and 21 (Figs. 1 and 2). The magnitude of these jumps is similar to those during the last Termination (27), when the CO₂ level and temperature are similar to those of DO-19, 20, and 21 (65 to 90 kya). During the intervening period (20 to 65 kya), this type of variability is not as apparent in our record. The origin of these brief periods of elevated CO₂ is not clear, but may be related to increases in sea surface temperature in the Northern Hemisphere or release of CO₂ from the terrestrial biosphere by respiration, associated with abrupt warming in Greenland.

Another notable feature is the rapid decrease in CO₂ concentration of ~43 ppm at ~68 kya [Greenland Ice Sheet Project 2 (GISP2) time scale] after DO-19 (Figs. 1C and 4). The magnitude of the CO₂ drop is about half the total CO₂
variations during long-term glacial-interglacial cycles. The fastest rate of decrease during the event is ~11 ppm/ka, but the true value could have been even larger. A similar decrease of ~40 ppm at this time is also observed in low-resolution Vostok (28) and Dome Fuji records (29). A large sea-level drop appears to predate the CO2 decline (Fig. 4). It is notable that a rapid increase of dust flux occurred in the equatorial Pacific and Antarctica at around the same time (30, 31).

Our results support the idea that atmospheric CO2 concentration is controlled by oceanic processes, especially those associated with proxies for the reduction of stratification in the Southern Ocean, but also affected by the Northern Hemisphere climate. Reductions in overturning circulation in the Northern Hemisphere appear to be associated with increases in atmospheric CO2. On the basis of these data, if global warming causes a decrease in the overturning circulation (32), we might expect a positive feedback from additional CO2 emissions to the atmosphere. However, the application of those observations to the future carbon cycle should be done cautiously because of differences between glacial and interglacial climate boundary conditions (17). It is likely that higher-resolution records of CO2 will reveal more details about precise timing between Antarctic and Greenland temperature and atmospheric CO2.

References and Notes
10. Materials and methods are available as supporting material on Science Online.