cause of the inhomogenity of the signals (on the order of ±1000 years) but distinct. Because of the different nature of the Greenland and Antarctic signals, the age shift for the correlation maximum is smaller than that resulting from comparing the timing of initial warming in both records.
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Atmospheric CO_2 Concentrations over the Last Glacial Termination

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A record of atmospheric carbon dioxide (CO_2) concentration during the transition from the Last Glacial Maximum to the Holocene, obtained from the Dome Concordia, Antarctica, ice core, reveals that an increase of 76 parts per million by volume occurred over a period of 6000 years in four clearly distinguishable intervals. The close correlation between CO_2 concentration and Antarctic temperature indicates that the Southern Ocean played an important role in causing the CO_2 increase. However, the similarity of changes in CO_2 concentration and variations of atmospheric methane concentration suggests that processes in the tropics and in the Northern Hemisphere, where the main sources for methane are located, also had substantial effects on atmospheric CO_2 concentrations.

The concentration of atmospheric CO_2 has been increasing steadily since the beginning of industrialization, from ~280 parts per million by volume (ppmv) to its present value of ~368 ppmv (*1–4*). By investigating earlier, natural CO_2 variations, we expect to obtain information about feedbacks between the carbon cycle and climate and also the possible impact of the anthropogenic CO_2 on the climate system. The transition from the Last Glacial Maximum (LGM) to the Holocene, during which CO_2 increased by ~40%, is a key period for such investigations.

The ice core record from Vostok, Antarctica, covering the past 420,000 years, shows increases of the CO_2 concentration between 80 and 100 ppmv for each of the past four glacial terminations (*5*). The increase during the last termination is well established on the basis of various polar ice cores from both hemispheres (*6–10*). However, not all ice cores are well suited to investigate the details of such an increase. Some CO_2 records, especially those from Greenland ice cores, are compromised by the production of CO_2 by chemical reactions between impurities in the ice (*11–13*). Ice cores from Antarctica are less affected, but a small amount of in situ CO_2 production by chemical reactions cannot be excluded for all Antarctic ice cores and all climatic periods (*14, 15*). CO_2 records from Vostok and Taylor Dome are thought to be the most accurate (*5, 10, 16*). However, the time resolution of these two records is too low to provide a history of CO_2 changes that shows the detailed evolution of atmospheric CO_2 over the last glacial termination.

Here, we present a record from the Dome Concordia (Dome C), Antarctica (75°06′S, 123°24′E), ice core drilled in the frame of the European Project for Ice Coring in Antarctica (EPICA) during the field season 1998–99. We measured CO_2 in a total of 432 samples from 72 different depth intervals, between depths of 350 and 580 m, covering the period from 22 to 9 ky B.P. (ky B.P. is thousand years before present, where present is chosen as A.D. 1950). For each depth level, six samples were measured on a 60- to 100-mm length interval. On the same core, 74 methane measurements were performed. The analytical methods are described in (*17*).

The age scale for the ice, as well as for the enclosed air (which is younger than the surrounding ice because it is enclosed at the bottom of the firn layer), is based on the time scale by Schwander *et al.* (*18*). The uncertainty of the absolute time scale for the ice is estimated to ±200 years back to 10 ky B.P. and up to ±2000 years back to 41 ky B.P. The gas-ice age difference (Δage) is calculated with a firn densification model. The value of Δage is ~2000 years in the Holocene, increasing to ~5500 years during the LGM, and has an estimated uncertainty of ~10%.

The main feature of the CO_2 record (Fig. 1) is an increase from a mean value of 189 ppmv between 18.1 and 17.0 ky B.P. (*19*) to a mean value of 265 ppmv between 11.1 and 10.5 ky B.P. (beginning of the Holocene). The increase of 76 ± 1 ppmv occurs in four distinct intervals. From 17.0 to 15.4 ky B.P. (interval I), CO_2 increases from 189 to 219 ppmv at a mean rate of 20 ppmv/ky. From 15.4 to 13.8 ky B.P. (interval II), CO_2 rises from 219 to 231 ppmv at a rather constant rate of 8 ppmv/ky before a rapid increase of ~8 ppmv within three centuries at 13.8 ky B.P. Between 13.8 and 12.3 ky B.P. (interval III), a small decrease from 239 to 237 ppmv occurs at a rate of

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about –1 ppmv/ky. From 12.3 to 11.2 ky B.P. (interval IV), the CO_2 concentration rises from 237 to 259 ppmv at a rate of 20 ppmv/ky, followed by a rapid increase of ~6 ppmv in about two centuries at 11.2 ky B.P. The rapid increases at the end of intervals II and IV (*20*) occur within a time interval that is comparable to the age distribution of the air enclosed in the ice owing to the enclosure process at the firn-ice transition (the width of age distribution is on the order of 10% of the Δage value). Therefore, the increase of CO_2 could have occurred in even less then a few centuries.

The possibility of CO_2 enrichment by chemical reactions between impurities in the Dome C ice core has been carefully investigated. The most likely sources are acid-carbonate reactions and the oxidation of organic compounds (*11, 15, 21*). We found no positive correlation between Ca^{2+} (a qualitative indicator for carbonate) or H_2O_2 concentrations [both measured with continuous flow analysis technique (*22*)] and the CO_2 values. Also, our results agree well with less-detailed records from other Antarctic ice cores, with different impurity concentrations, within the error limits (*17*). The strongest argument against CO_2 production by chemical reactions is that the scatter of CO_2 values from neighboring samples is in agreement with the analytical uncertainty. We thus conclude that our record is an accurate representation of the atmospheric CO_2 concentrations.

Comparison of the deuterium abundance of the ice (δD, a proxy for surface air temperature) (*23*) and the CO_2 record (Fig. 1) suggests a close correlation between both parameters. The correlation coefficient r between 11.2 and 17.0 ky B.P. is 0.85 (*17*). Shifting the time scales of the two records relative to each other showed that the correlation coefficient reaches a maximum of r = 0.94 at a time lag of the CO_2 record of 410 years. Considering the uncertainties of the gas-ice age difference of 200 to 550 years, this lag is not significant and can also be a consequence of an overestimated gas-ice age difference (*18*).

To define the points at which temperature and CO_2 began to rise, we selected the crossing points of linear fits of the records and obtained ages of 17,000 ± 200 years for the start of the CO_2 increase and 17,800 ± 300 years for the start of the δD increase. We found that the start of the CO_2 increase thus lagged the start of the δD increase by 800 ± 600 years, taking the uncertainties of the gas-ice age difference and the determination of the increases into account. This agrees with the estimates found in the ice cores from Taylor Dome and Byrd (*10*). The estimated time lag is small in comparison with the 6000-year duration of the closely tied temperature and CO_2 concentration increases and does not cast doubt on the importance of CO_2 as an amplification factor of the temperature increase.

A precise comparison of CO_2 and methane (Fig. 1) is possible because there is no age offset between the two records. The record of the methane concentration during the transition can also be subdivided in four distinct intervals, all synchronous with the intervals of the CO_2 record.

Interval I is characterized by the synchronous start of the CO_2 and methane increases. Interval II shows a reduced CO_2 increase rate and a plateau of the methane concentration. No obvious changes are observed in the trend of the δD record of Dome C (Fig. 1) or in Greenland stable isotope records from intervals I to II (*24*). The transition between intervals II and III, characterized by a fast CO_2 rise, shows a corresponding fast increase in methane concentration. Interval III shows a slow and small decrease in the CO_2 concentration, whereas the methane is almost at the early Holocene concentration. Interval III corresponds to the Bølling/Allerød (B/A) warm phase in the North Atlantic region and to the Antarctic Cold Reversal (ACR) observed in Antarctica (*25–27*). Interval IV, during which a continuous CO_2 increase is terminated by a pronounced CO_2 rise at the transition to the Holocene, exhibits a methane concentration drop of ~200 parts per billion by volume (ppbv), returning to concentrations like those of interval II. Interval IV corresponds to the Younger Dryas

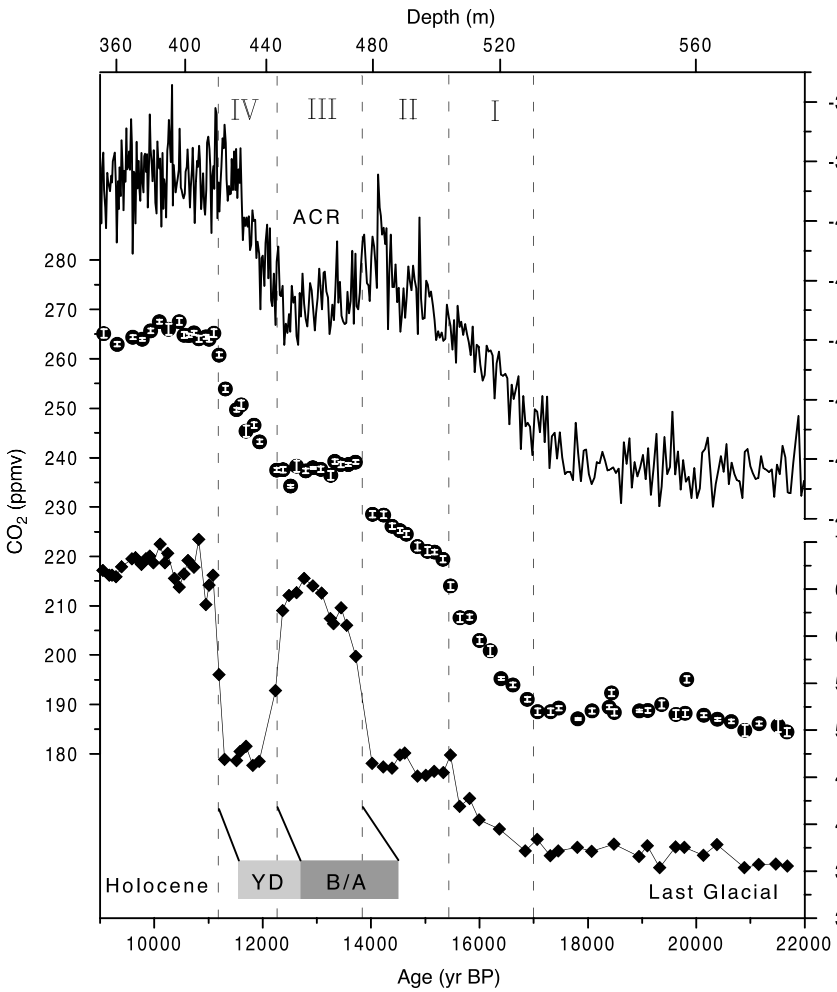

Fig. 1. The solid curve indicates the Dome C δD in the ice as a proxy for local temperature (*23*). Solid circles represent CO_2 data from Dome C (mean of six samples; error bars, 1σ of the mean). Diamonds show methane data from Dome C (the 1σ uncertainty is 10 ppbv). The time scale used for the gas-ice age is from work by Schwander *et al.* (*18*) (the depth at the top of the figure is only valid for the CO_2 and methane records). In the CO_2 and methane records, four intervals (I through IV) can be distinguished during the transition. The δD record is highly correlated with the CO_2 record, with the exception that the increased rates during intervals I and II are not significantly different in the deuterium record. The YD and the B/A events recorded in Greenland ice cores are indicated by shaded bars according to the GRIP time scale. Comparisons of the methane record with that of GRIP demonstrate that the YD corresponds to interval IV and the B/A event corresponds to interval III.

(YD) epoch in the North Atlantic region and to the warming interval after the ACR in Antarctica.

Data from Vostok suggest an important role of the Southern Ocean in regulating the glacial-interglacial CO_2 changes (*5*). This role is confirmed by measurements from Taylor Dome for shorter time intervals in the last glaciation (*16*). The CO_2 increase in interval I, which occurred before any substantial warming in the Northern Hemisphere, is consistent with the present view of the role of the Southern Hemisphere for causing the CO_2 increase.

Methane starts to increase parallel to CO_2 in interval I. The methane increase is in agreement with the Greenland Ice Core Project (GRIP) record (*28*). The parallelism of the methane and CO_2 increase in interval I is somewhat surprising because the causes for methane variations are certainly different from those for CO_2. It is assumed that methane concentration changes were mainly due to changes of the extent and activity of wetlands in northern latitudes and the tropics (*29*). No substantial variations can be seen in the GRIP stable isotope record during this time period, but a small change of the methane production in low and mid-latitudes is not necessarily recorded in a Greenland temperature record. There is no obvious cause of the reduced rates of growth in CO_2 and methane between intervals I and II visible in the stable isotope records of Dome C or of GRIP.

The fast increases of CO_2 and methane concentrations between intervals II and III, at ~13.8 ky B.P. according to the Dome C time scale, correspond to the fast warming in the Northern Hemisphere observed at 14.5 ky B.P. on the GRIP time scale. This warming was probably caused by enhanced formation of North Atlantic Deep Water (NADW) (*30*), suggesting that the sudden CO_2 increase could have been caused by changes in thermohaline circulation. The methane increase, on the other hand, is thought to have been caused by an intensified hydrological cycle during the B/A warm phase, which led to an expansion of wetlands in the tropics and northern latitudes.

CO_2 decreased slightly during interval III and then increased during interval IV. The methane concentration follows the temperature evolution of the Northern Hemisphere in intervals III and IV as expected. The accelerated CO_2 increase at the end of interval IV probably is connected to the fast warming in the Northern Hemisphere rather than to any climate or environmental evolution in the Southern Hemisphere, because it is synchronous with the methane increase.

These data support the idea that the Southern Ocean was an important factor in regulating the CO_2 concentration during the last transition. However, the fast increases between intervals II and III and at the end of interval IV show that additional mechanisms in the Northern Hemisphere influenced CO_2, presumably through changes in NADW formation.

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Evolution of Universal Grammar

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Universal grammar specifies the mechanism of language acquisition. It determines the range of grammatical hypothesis that children entertain during language learning and the procedure they use for evaluating input sentences. How universal grammar arose is a major challenge for evolutionary biology. We present a mathematical framework for the evolutionary dynamics of grammar learning. The central result is a coherence threshold, which specifies the condition for a universal grammar to induce coherent communication within a population. We study selection of grammars within the same universal grammar and competition between different universal grammars. We calculate the condition under which natural selection favors the emergence of rule-based, generative grammars that underlie complex language.

Language consists of words and rules. The finite ensemble of memorized words is called the mental lexicon, whereas the set of rules is called the mental grammar of a person (*1, 2*). Grammar is the computational system (*3*) that is essential for creating the infinite expressibility of human language. Children acquire their mental grammar spontaneously and without formal training. Children of the same speech community reliably learn the same grammar. Exactly how the mental grammar comes into a child's mind is a puzzle. Children have to deduce the rules of their native language from sample sentences they receive from their parents and others. This information is insufficient for uniquely determining the underlying grammatical principles (*4*). Linguists call this phenomenon the "poverty of stimulus" (*5*) or the "paradox of language acquisition" (*6*). The proposed solution is universal grammar (*7*).

Universal grammar consists of (i) a mech-

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