cause of the inhomogeneity 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.


R E P O R T S

Atmospheric CO₂ Concentrations over the Last Glacial Termination

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A record of atmospheric carbon dioxide (CO₂) 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 CO₂ concentration and Antarctic temperature indicates that the Southern Ocean played an important role in causing the CO₂ increase. However, the similarity of changes in CO₂ 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 CO₂ concentrations.

The concentration of atmospheric CO₂ 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 CO₂ variations, we expect to obtain information about feedbacks between the carbon cycle and climate and also the possible impact of the anthropogenic CO₂ on the climate system. The transition from the Last Glacial Maximum (LGM) to the Holocene, during which CO₂ 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 CO₂ 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 CO₂ records, especially those from Greenland ice cores, are compromised by the production of CO₂ by chemical reactions between impurities in the ice (11–13). Ice cores from Antarctica are less affected, but a small amount of in situ CO₂ production by chemical reactions cannot be excluded for all Antarctic ice cores and all climatic periods (14, 15). CO₂ 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 CO₂ changes that shows the detailed evolution of atmospheric CO₂ 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 CO₂ 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 AD. 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 firm 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 firm 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 CO₂ 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), CO₂ 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), CO₂ 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 CO₂ 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 CO₂ could have occurred in even less than a few centuries.

The possibility of CO₂ 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 Ca²⁺ (a qualitative indicator for carbonate) or H₂O₂ concentrations [both measured with continuous flow analysis technique (22)] and the CO₂ 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 CO₂ production by chemical reactions is that the scatter of CO₂ values from neighboring samples is in agreement with the analytical uncertainty. We thus conclude that our record is an accurate representation of the atmospheric CO₂ concentrations.

Comparison of the deuterium abundance of the ice (δD, a proxy for surface air temperature) (23) and the CO₂ 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 CO₂ 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 CO₂ 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 CO₂ increase and 17,800 ± 300 years for the start of the δD increase. We found that the start of the CO₂ 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 ages 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 CO₂ concentration increases and does not cast doubt on the importance of CO₂ as an amplification factor of the temperature increase.

A precise comparison of CO₂ 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 CO₂ record.

Interval I is characterized by the synchronous start of the CO₂ and methane increases. Interval II shows a reduced CO₂ 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 CO₂ rise, shows a corresponding fast increase in methane concentration. Interval III shows a slow and small decrease in the CO₂ concentration, whereas the methane is almost at the early Holocene concentration. Interval IV corresponds to the Bolling/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 CO₂ increase is terminated by a pronounced CO₂ 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 CO₂ 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 CO₂ and methane records). In the CO₂ and methane records, four intervals (I through IV) can be distinguished during the transition. The δD record is highly correlated with the CO₂ 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.](http://science.sciencemag.org/)
and III and at the end of interval IV show that additional mechanisms in the Northern Hemisphere influenced CO₂, presumably through changes in NADW formation.

**References and Notes**


17. Supplementary information concerning procedures or assumptions is available at www.sciencemag.org/cgi/content/full/291/5501/112/DC1.

18. J. Schwander et al., in preparation.
19. Throughout the remainder of the report, the precision of the ages is given in decimals of ky B.P. in order to facilitate the identification in Fig. 1. Nevertheless, the uncertainty in the absolute time scale remains as described in the text.
20. The available CO₂ data also suggest a small jump at the transition between intervals I and II, but this must be confirmed by further measurements.
31. We thank O. Marchal, F. Joos, J. Schwander, J. Chappellaz, and N. Shackleton for helpful comments. This work is a contribution to EPICA, a joint European Science Foundation/European Commission (EC) scientific program, funded by the EC under the Environment and Climate Programme (1994–98) contract ENV4-CT95-0074 and by national contributions from Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland, and the United Kingdom. This is EPICA publication no. 23. The measurements were supported by the Swiss NSF, the University of Bern, and the "Bundesamt für Energie."

19 August 2000; accepted 17 November 2000

### 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.

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...would lead to an expansion of wetlands in the tropics and northern latitudes.

CO₂ 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 CO₂ 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 during the B/A warm phase, which led to an expansion of wetlands in the tropics and northern latitudes.