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Last interglacial atmospheric CO_2 changes from stomatal index data and their relation to climate variations

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Abstract

A high-resolution atmospheric CO_2 reconstruction based on stomatal index data obtained from *Betula* and *Quercus* leaf fragments extracted from the Danish Hollerup lake sediment section provides a unique insight into last interglacial CO_2 dynamics. According to pollen stratigraphic correlations the CO_2 record covers the first c. 7400 years of the Eemian, as palaeobotanically defined in northwestern Europe. The first c. 3000 years of the reconstruction are characterised by centennial to millennial CO_2 variability in the interval 250–290 ppmv, while the remaining part of the record is generally more stable with slightly higher values (290–300 ppmv). According to pollen stratigraphic correlations this shift in CO_2 dynamics is coincident with the end of the early Eemian climatic optimum in northwestern Europe. Pollen data from this region indicate that early Eemian CO_2 instability may be linked to vegetation succession following deglaciation in Europe, but vegetation dynamics on other northern continents were probably also important. In addition, palaeoceanographic records from the Nordic seas indicate an influence of oceanic processes on the reconstructed Eemian CO_2 evolution. A 300-year period of rapid CO_2 oscillations immediately before the establishment of stable conditions is synchronous with a dry and cool event previously inferred from proxy data from the same sediment sequence, suggesting that this was a climatic event of regional or global significance. The presented CO_2 reconstruction is in general agreement with previous ice core and stomatal-based CO_2 data, although a larger variability compared with Vostok ice core data is evident. This may be explained partly by the different resolution of the two records and the inherent smoothing of ice core gas records.

Keywords: CO_2; last interglacial; Eemian; climate; stomata; leaves

1. Introduction

Data from the Antarctic Vostok ice core have revealed that atmospheric carbon dioxide plays an important role as an amplifier of climatic changes over glacial–interglacial time scales (Fischer et al.,

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1999; Petit et al., 1999; Raynaud et al., 2000; Shackleton, 2000; Mudelsee, 2001). The deduced sequence of events is that a change in orbital parameters affecting summer insolation at high northern latitudes directly influences temperature conditions at Earth's surface. Reorganization of the global carbon cycle caused by this initial temperature change then leads to amplification of the temperature response through a change in the atmospheric concentration of CO_2 (and methane). The temperature change resulting from this positive feedback is most pronounced at high northern and southern latitudes and therefore an important control of global ice volume. The Vostok ice core has allowed detection of the link between atmospheric greenhouse gases and climate over the past four glacial–interglacial cycles and a new ice core drilled at Dome C in Antarctica will extend this over three more cycles (EPICA community members, 2004).

Human activity has recently introduced a new role for atmospheric CO_2 in the climate system; burning of fossil fuels and the resulting rapid CO_2 increase has made atmospheric CO_2 into an important forcing factor that is itself not influenced by climate. This situation is unique to the last 150–200 years, although it has been suggested that human activities (agriculture and forest clearance) already started to impact on atmospheric CO_2 concentrations 8 kyr ago (Ruddiman, 2003). The latter proposition is partly based on the observation that the Holocene CO_2 evolution is different from those of earlier interglacials. Like the Holocene, the three previous interglacials began with a pronounced CO_2 peak (Petit et al., 1999). However, following a decline over c. 3 kyr, Holocene CO_2 concentrations started an increasing trend that, with minor oscillations, continued up to the onset of industrialisation (Indermühle et al., 1999), a feature not seen in previous interglacials. The CO_2 evolution following the early maximum was not identical between earlier interglacials but, according to the Vostok record, there was in no case a reverse trend towards higher CO_2 concentrations.

The study of proxy records from previous interglacials is important to increase our understanding of interglacial climate dynamics without human interference and it may also help us to identify anthropogenic influence during the Holocene. The penultimate interglacial, approximately corresponding to marine isotope stage (MIS) 5e dated to c. 130–116 ka (Kukla et al., 2002), offers the possibility to study interglacial climate records from a wide array of archives and regions at relatively high resolution. Prior to MIS 5e, terrestrial interglacial records become more sparse and fragmented and temporal resolution generally becomes lower for all types of archives. Moreover, the last interglacial has been a major focus of interest within palaeoclimate research over the last decade, an interest spurred by indications of marked interglacial instability in a Greenland ice core (GRIP members, 1993). Although ambiguous (Grootes et al., 1993; North Greenland Ice Core Project Members, 2004), these data were the starting point of an intensive search for evidence of rapid climate changes in marine and terrestrial records. So far, the resulting data tend to suggest that the last interglacial was less stable than the Holocene, at least at high northern latitudes (e.g., Fronval et al., 1998), but it is not known what role CO_2 may have played for this relative instability.

Because of the low ice accumulation rate at Vostok, the last interglacial section of this CO_2 record is of low resolution (Petit et al., 1999), with wide age distribution of the enclosed air. As a consequence of diffusion through the firn layer during enclosure, air bubbles in interglacial sections of this core have an age distribution of c. 300 years (Barnola et al., 1991). In addition, the dating uncertainty, estimated to be $\pm$10 kyr in the relevant interval (Petit et al., 1999), makes it difficult to directly relate the Vostok CO_2 record to palaeoclimatic records. Of the alternative CO_2 proxies available, the stomatal frequency method is the most direct and also has the capability to reconstruct CO_2 dynamics at the century scale (Royer, 2001; Rundgren and Beerling, 2003). It has previously been applied to leaves of last interglacial age and yielded results in general agreement with Vostok data (Rundgren and Bennike, 2002). The method rests on the inverse relationship between stomatal frequency of terrestrial plant leaves and CO_2 partial pressure as revealed by historic data sets and controlled experiments (Woodward, 1987; Woodward and Bazzaz, 1988). The level of atmospheric CO_2 determines the number of cells that develop into stomata and this is set during the early stages of leaf development. Consequently, the number of stomata relative to the sum of stomata and epidermal cells, usually referred to as stomatal index (SI), constitutes a reliable proxy for atmospheric CO_2 (Beerling, 1999; Royer, 2001).