Century-scale changes of atmospheric CO_2 during the last interglacial

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ABSTRACT

The crucial role of atmospheric CO_2 in glacial-interglacial transitions is demonstrated by recent ice-core studies that highlight the importance of accurate CO_2 records for our understanding of Quaternary climate dynamics. Previous estimates of CO_2 levels during the last interglacial stage (the Eemian) relied on measurements on air trapped in the Antarctic Vostok ice core. Due to uncertainties associated with in situ chemical alteration and gas diffusion, there is a need for independent estimates of past CO_2 levels. Here we report 33 Eemian CO_2 estimates based on the stomatal index of *Salix herbacea* L. leaves preserved in Greenland sediments. We reconstruct Eemian CO_2 levels centered on 250–280 parts per million by volume (ppmv), in general agreement with ice-core data. Two deviating (lower) stomatal estimates may reflect diffusional smoothing of Vostok CO_2 data and indicate century-scale Eemian CO_2 variability.

Keywords: Eemian, CO_2, leaves, *Salix*, Greenland.

INTRODUCTION

Recent analyses of the Vostok ice-core record, which encompasses the four last glacial-interglacial cycles, suggest that changes in Southern Hemisphere temperature led atmospheric CO_2 variations, which in turn led global ice-volume changes (Fischer et al., 1999; Petit et al., 1999; Raynaud et al., 2000; Shackleton, 2000; Mudelsee, 2001). These observations point to CO_2 as an amplifier of orbitally forced temperature changes. If representative for interglacial conditions, the Eemian (ca. 115–130 ka; Martinson et al., 1987) probably makes our best analogue for the present interglacial (the Holocene). Therefore, a better understanding of Eemian climate and carbon cycle dynamics may give clues to future climate change, e.g., how and when the next glacial will be initiated. Its merit as a standard interglacial has, however, been questioned because records suggest that climate varied far more in the Eemian compared to the Holocene (GRIP Members, 1993; Field et al., 1994; Fronval and Jansen, 1996), while other studies have advocated the traditional concept of a climatically relatively stable Eemian (McManus et al., 1994; Litt et al., 1996; Adkins et al., 1997). Continued efforts to improve correlation between terrestrial and marine records (Björck et al., 2000) are needed to reconcile this conflicting evidence.

Although Eemian CO_2 levels have been estimated from marine carbon isotope data (Shackleton et al., 1983), the Vostok ice-core record constitutes our primary source of information on Eemian CO_2 levels. This record reflects atmospheric CO_2 concentrations within the range of 261–287 parts per million by volume (ppmv) (Petit et al., 1999). There are, however, uncertainties associated with the use of ice cores for atmospheric CO_2 reconstruction (Tschumi and Stauffer, 2000). It is now recognized that CO_2 may be produced in situ by chemical reactions between impurities (carbonates and organic compounds) in the ice, but because of the relatively low dust content in Antarctic ice, especially in interglacial intervals (Petit et al., 1999), this effect is likely to be small for the Vostok record. In addition, CO_2 may be depleted after enclosure in ice, mainly as a consequence of clathrate formation. Accurate dating of air bubbles is complicated by air diffusion through the firn layer during enclosure, making the air younger than the surrounding ice. The Vostok time scale, which is based on modeling of ice flow and ice accumulation, has an estimated accuracy of ±10 k.y. or less for most of the record, and better than ±5 k.y. for the past 110 k.y. (Petit et al., 1999). More important, diffusion results in an inherent smoothing of ice-core CO_2 records, because each bubble represents a period ranging from decades to several centuries, depending on sample age and site characteristics. This effect is significant at low-accumulation sites such as Vostok, where it results in an age distribution of the enclosed air of ~300 yr in the relevant core section (Barnola et al., 1991).

Because of these uncertainties, as well as the general lack of CO_2 data, there is a need for independent estimates of Eemian CO_2 levels. Stomatal frequency analysis of fossil leaves preserved in sediments is an emerging approach that can provide high-resolution atmospheric CO_2 records on time scales from decades to millions of years (Wagner et al., 1996, 1999; McElwain et al., 1999; Rundgren and Beerling, 1999; Royer, 2001). This method is based on the inverse relationship between stomatal frequency of terrestrial plant leaves and CO_2 partial pressure (Woodward, 1987; Woodward and Bazzaz, 1988). By applying the stomatal index (SI; proportion of leaf surface cells that are stomata), it is possible to minimize the impact of variations in irradiance, relative humidity, and water supply, which are environmental factors known to influence leaf expansion and stomatal density (SD; number of stomata per unit area) (Beerling, 1999; Royer, 2001). The CO_2 data presented here are based on the stomatal index of Eemian dwarf willow (*Salix herbacea* L.) leaves. Both the SD and SI of this species show clear response to atmospheric CO_2 variations, and it has previously been successfully used for CO_2 reconstruction during the last glacial termination and the Holocene (Beerling et al., 1995; Rundgren and Beerling, 1999).

MATERIAL AND METHODS

Our samples were collected in 1990–1994 at sites stratigraphically investigated in connection with the PONAM (Polar North Atlantic Margins: Late Cenozoic Evolution) project (Funder et al., 1994). They derive from beds of shallow-marine, deltaic, and fluvial sediments found in many places along the west and south coast of Jameson Land (Fig. 1). Remains of marine and terrestrial plants and animals recovered from these sediments reflect sea-surface and mean summer air temperatures 3–4 °C higher than during the warmest part of the Holocene (Funder et al, 1994; Bennike and Böcher, 1994), which suggests that they were deposited under interglacial conditions. Correlation of these sedimentary units between sites is based on their thermophilous faunas and floras, and they are attributed to the Langelandselv, believed to correlate with the Eemian, an interpretation supported by numerous luminescence dates (Funder et al., 1994). Coastal Jameson Land was glaciated three times during the last glacial stage, but interglacial sediments are preserved in many areas.

We analyzed *S. herbacea* leaves from 33 interglacial sediment samples (altitudinal span 9.5–24.0 m above sea level) collected at 21 sites that span ~70 km along the coast of Jameson Land (Fig. 1). More than one sample (maximum five), collected at different levels within the interglacial unit, was available for six of the sites. We do not know from which part of the Eemian the samples come, and the relationship within the Eemian between samples from different sites is unknown.

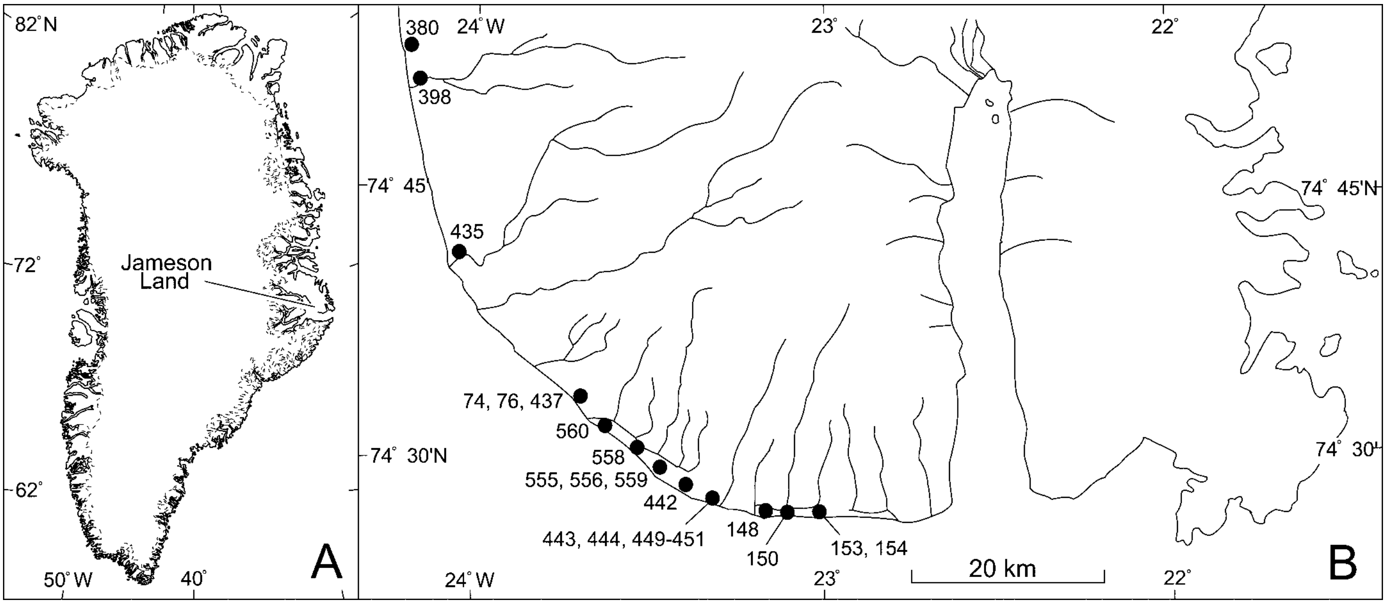

Figure 1. A: Map of Greenland showing location of Jameson Land. B: Map of Jameson Land; dots indicate sample sites.

The number of analyzed leaves (or leaf fragments > one-half) per sample varied from 1 to 37, and 5 stomatal index measurements were made per leaf surface using an epifluorescence microscope (×400 magnification). Veinal and marginal areas were avoided to minimize SI variability (Poole and Kürschner, 1999). Stomatal index was calculated as $SI = [SD/(SD + ED)] \times 100$ (ED = epidermal cell density, mm^{-2}). For calibration of the Eemian SI data we applied inverse regression (Draper and Smith, 1981) to a previously published modern training set for *S. herbacea* (Rundgren and Beerling, 1999; Fig. 2). Because all interglacial samples were collected within a narrow altitudinal range close to present sea level, it was possible to transform our calibrated CO_2 data (in Pa) into equivalent volume concentration values (in ppmv) by multiplication with a factor of 10, enabling direct comparison with ice-core values.

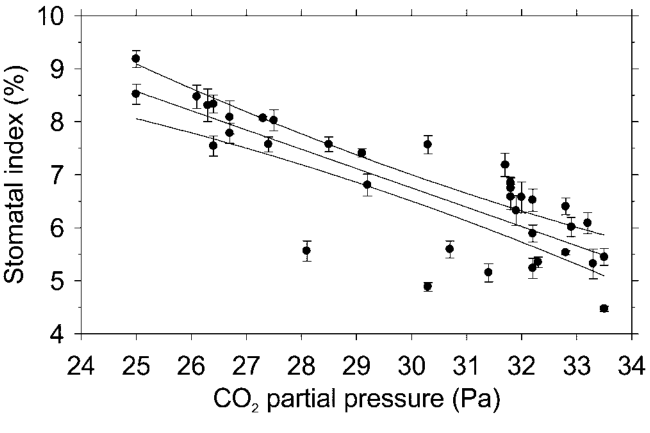

Figure 2. Relation between stomatal index of *Salix herbacea* and atmospheric CO_2 partial pressure (Rundgren and Beerling, 1999) used for calibration of Eemian leaf data. Modern training set includes samples from Greenland, Iceland, Norway, Sweden, Austria, and UK collected in field and from herbaria. CO_2 partial pressure variability represented by these samples is attributed to combination of rise in atmospheric CO_2 concentration (1900–1998) and altitudinal gradient of 100–2670 m above sea level. Statistics for linear regression (shown with 95% confidence intervals): $n = 36$ (5 leaves per sample; error bars indicate sample standard errors), intercept = 17.679, slope = −0.364, $R^2 = 0.68$, $P < 0.001$.

RESULTS AND DISCUSSION

We reconstruct Eemian CO_2 concentrations of 208–287 ppmv, the majority of estimates being within 250–280 ppmv (Fig. 3). This is in good agreement with Vostok data (Eemian range 261–287 ppmv), and only two samples (96046 and 87512) are significantly outside the Vostok range. Although stomatal-based absolute values below 250 ppmv should be regarded as provisional because they are outside the CO_2 gradient of the calibration data set (Fig. 2) and consequently rely on extrapolation of the regression line, these low estimates undoubtedly reflect Eemian CO_2 levels lower than those measured in the Vostok ice core. This deviation could be explained by the inherent smoothing (the ~300 yr gas age distribution) of the ice-core CO_2 record due to diffusion. Accordingly, the stomatal method, with its capacity to detect decadal to century-scale CO_2 variations, may have registered previously unrecorded short-lived Eemian intervals of low CO_2 levels.

Early Holocene century-scale CO_2 shifts are suggested by stomatal evidence (Wagner et al., 1999), and short-term CO_2 variability is also apparent in a stomatal-based CO_2 reconstruction for the past 9 k.y. (Rundgren and Beerling, 1999). Further research is needed to validate these results, but the two low Eemian CO_2 values presented here appear to be consistent with these indications of interglacial carbon cycle instability. Until recently, the preindustrial part of the Holocene was considered a period of stable atmospheric CO_2 conditions, but this view has been challenged by ice-core and stomatal data reflecting millennial-scale Holocene CO_2 variations (Indermühle et al., 1999; Rundgren and Beerling, 1999). Such variability is also suggested for the Eemian by the Vostok record (Fischer et al., 1999; Petit et al., 1999), and it may be that Eemian CO_2 levels were variable on shorter time scales, as indicated by our data. Clearly, the use of the Eemian paleoclimatic record as an analogue for the Holocene requires a better understanding of both Eemian and Holocene climate and carbon cycle dynamics.

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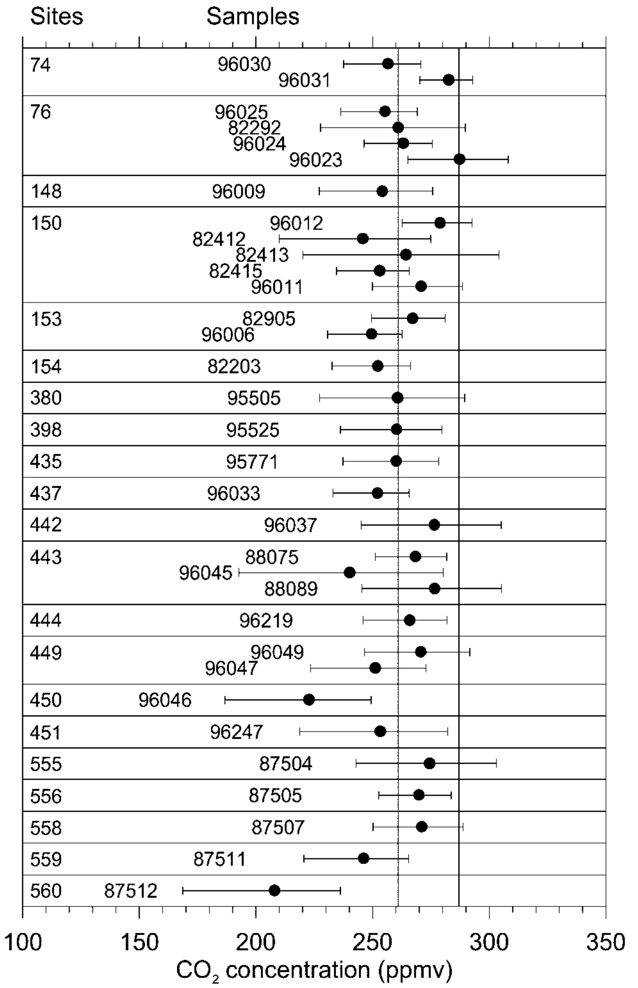

Figure 3. Reconstructed atmospheric CO_2 concentration values, with 95% confidence limits, for 33 Eemian samples collected on Jameson Land, East Greenland. Vertical lines delimit range of Eemian CO_2 estimates based on measurements on air trapped in Vostok ice core (Petit et al., 1999).

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