A role for atmospheric CO_2 in preindustrial climate forcing

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Complementary to measurements in Antarctic ice cores, stomatal frequency analysis of leaves of land plants preserved in peat and lake deposits can provide a proxy record of preindustrial atmospheric CO_2 concentration. CO_2 trends based on leaf remains of *Quercus robur* (English oak) from the Netherlands support the presence of significant CO_2 variability during the first half of the last millennium. The amplitude of the reconstructed multidecadal fluctuations, up to 34 parts per million by volume, considerably exceeds maximum shifts measured in Antarctic ice. Inferred changes in CO_2 radiative forcing are of a magnitude similar to variations ascribed to other mechanisms, particularly solar irradiance and volcanic activity, and may therefore call into question the concept of the Intergovernmental Panel on Climate Change, which assumes an insignificant role of CO_2 as a preindustrial climate-forcing factor. The stomata-based CO_2 trends correlate with coeval sea-surface temperature trends in the North Atlantic Ocean, suggesting the possibility of an oceanic source/sink mechanism for the recorded CO_2 changes.

carbon cycle | global warming | past millennium | stomata

It is increasingly realized that temperature-sensitive proxy records inferred from tree rings, lake deposits, and historical documents corroborate occurrences of significant preindustrial air-temperature fluctuations during the last millennium (1–5). Also, the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC) (6) now cautiously presents a whole range of historical temperature reconstructions instead of favoring the earlier "hockey-stick" graph of the *Third Assessment Report* of the IPCC (7). The reconstructed fluctuations show largely differing amplitudes and timing. It is obvious that individual proxy temperature curves are not parallel to the generally accepted atmospheric CO_2 curve for the last 1,000 years, which is characterized by a very low degree of preindustrial variability. This curve is based on CO_2 records from Antarctic ice cores, which suggest that until the onset of industrialization in the 19th century, atmospheric CO_2 concentration (expressed as mixing ratio) varied by not more than 12 parts per million by volume (ppmv) (8–12). Although modest negative CO_2 anomalies have been associated with the Little Ice Age (10, 11, 13, 14), the *Fourth Assessment Report* treats such variation as an insignificant forcing mechanism for generating preindustrial air-temperature changes (6), especially when compared with effects of changes in solar irradiance and explosive volcanic activity (15–18).

Estimates of preindustrial CO_2 levels are available not only from Antarctic ice but also from leaves of land plants preserved in peat and lake deposits. Particularly in a wide variety of woody plants, the genetically controlled inverse relationship between numbers of leaf-stomata (gas exchange pores) and ambient CO_2 concentration during the growth period (19) permits detection and quantification of past CO_2 changes by analyzing time-series data on stomatal frequency. The *Fourth Assessment Report* recognizes that stomatal frequency may provide reasonable constraints on past CO_2 variations on long geological time scales (10^5 to 10^8 years), but does not appreciate the applicability of this proxy for identifying decadal to millennial scale CO_2 changes during the Holocene Epoch (6). Yet, the integrity of short-term leaf-based CO_2 changes has been verified by fine-resolution analysis of the lifetime CO_2 responsiveness of individual trees (20) and by numerous other response curves based on well dated herbarium material and subfossil leaves, which consistently mimic the ongoing CO_2 increase apparent from Mauna Loa instrumental monitoring (21–24). Reproducibility of leaf-based CO_2 reconstructions is further demonstrated by coeval stomatal frequency records of taxonomically, geographically, and ecologically contrasting tree species, which confirm a coupling between CO_2 anomalies and early Holocene cooling events (25–28).

For the last millennium, pronounced preindustrial CO_2 variability has been reconstructed on the basis of needles of *Tsuga heterophylla* (western hemlock) from Mount Rainier, Washington, USA (29), and leaf remains of *Quercus robur* (English oak) from the southeastern part of the Netherlands (27, 30). The timing of the detected CO_2 changes is in good agreement with perturbations observed in Antarctic ice core records. Remarkably, however, reconstructed amplitudes >30 ppmv significantly exceed the maximum shifts of 12 ppmv CO_2 found in Antarctic ice. These discrepancies can be explained as an effect of smoothing resulting from diffusion processes in the firn layer at the site of the ice cores. Such processes lead to a reduced signal of the original atmospheric variability and may obscure high-frequency CO_2 variations (31). A modeling exercise, in which raw stomatal frequency data from *Q. robur* leaves were smoothed analogously to natural CO_2 smoothing in the firn, demonstrates that measured CO_2 mixing ratios in the Antarctic D47 core (9) considerably underestimate the actual atmospheric CO_2 variability during the 13th century (32). Apart from smoothing, diffusion is also responsible for a gas–ice age difference in ice cores, resulting in inadequate dating control with age uncertainties of up to 100 years for CO_2 data for the last millennium (11). Unlike ice-based CO_2 records, leaf-based records have the advantage of providing real-time data because the leaf-morphological CO_2 signature becomes permanently fixed at the moment of leaf development and is unaffected by burial processes.

The presence of high-amplitude CO_2 fluctuations as documented by stomatal frequency studies may falsify the IPCC concept that preindustrial temperature variability is constrained by relatively stable atmospheric CO_2 levels (6, 14, 33, 34). A higher degree of CO_2 variability during the last millennium must have resulted in a more prominent role for CO_2 as a forcing factor of air-temperature changes. In this study, the impact of CO_2 changes on preindustrial temperature is reassessed by quantifying the radiative forcing of the alternative CO_2 record

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derived from leaves of *Q. robur* and comparing its strength with solar and volcanic forcing components. The analysis focuses on the period between A.D. 1000 and 1500. At least in the Northern Hemisphere, this period includes a prolonged episode of climatic instability marking the transition between relatively warm weather conditions of the Medieval Climatic Optimum to the predominantly cooler conditions of the Little Ice Age (5, 30).

Results and Discussion

We used the rate of CO_2 responsiveness of oak leaves to derive an atmospheric CO_2 record for the first half of the last millennium (Fig. 1). Principal data are listed in supporting information (SI) Table S1. Data from individual sampling points exhibit varied values of standard deviation of stomatal indices (SIs) [0.01–4.04% SI (see *Materials and Methods*) and a mean standard deviation for the whole leaf assemblage of 1.56%]. Uncertainties in predicted CO_2 mixing ratios related to standard deviations of the SI range between 0.03 and 17.94 ppmv, with an average uncertainty for the whole dataset of 6.04 ppmv. However, the magnitude of the standard deviation does not show any unidirectional trends; low and high values are randomly distributed among successive sampling points. Therefore, despite varied uncertainty intervals, mean SI values (Fig. 1*A*) may be confidently applied for reconstructing mean atmospheric CO_2 trends.

Comparable to other stomata-based records (21, 25–28), reconstructed preindustrial CO_2 levels fluctuate between 319.2 and 292.3 ppmv with an average value of 311.4 ppmv. A normalized record is plotted in Fig. 1*C*. Calculated effects of the reconstructed multidecadal CO_2 fluctuations (up to 34 ppmv) on radiative forcing are shown in Fig. 1*E*. A declining trend from A.D. 1000 until A.D. 1200 by 0.5 W/m^2, interrupted by a temporary increase of 0.2 W/m^2 around A.D. 1100, is followed by a prominent increase of 0.7 W/m^2 that occurs between A.D. 1200 and 1300 as a result of a 34 ppmv CO_2 rise. After A.D. 1300 CO_2 forcing declines by 0.4 W/m^2. Calculations derived from the ECBILT-CLIO climate model indicate that the CO_2 changes would result in maximum global temperature anomalies of 0.25°C (Fig. 2).

Although the modeled temperature anomalies remain well within the range of maximum variability recognized by IPCC (6), they are difficult to match with the heterogeneous patterns exhibited by the individual proxy records that have been used to reconstruct time series of surface air-temperature variations on the Northern Hemisphere. Because actual temperature changes are generated by the sum of all forcing components, it is evident from Fig. 1*D* that any direct coupling between trends in atmospheric CO_2 and air temperature between A.D. 1000 and 1500 is likely to be masked by the reconstructed changes in solar forcing as well as by the prominent volcanic event of A.D. 1258 (35).

The supposedly modest atmospheric CO_2 variability during the last millennium recognized in the IPCC *Fourth Assessment Report* is generally related to changes in terrestrial carbon storage and/or variation in CO_2 solubility in the oceans (6, 14, 33, 34). It has been hypothesized that anthropogenic land-cover conversion in particular could have been critical in determining changes in distribution and size of terrestrial carbon sources and sinks (13, 14). Successive pollen assemblages from leaf-bearing sediments have enabled direct temporal correlation of stomata-based proxy CO_2 data and a high-resolution reconstruction of vegetation and medieval land use for the period between A.D. 1000 and 1500 (30). The 13th-century CO_2 increase corresponds to a well known period of massive forest clearing in Europe. In the pollen record, prolonged effects of the mid-14th century plague pandemic, known as the Black Death, are clearly reflected by a period of significant agricultural regression and concomitant reclamation of abandoned farmland by woody vegetation. It is conceivable that the Black Death may have been a contributing factor to a process of CO_2 decline during the 14th and 15th centuries (30), but modeling exercises suggest that plague-induced carbon storage on land could have accounted for only a CO_2 decrease of not more than ≈2 ppmv (14).

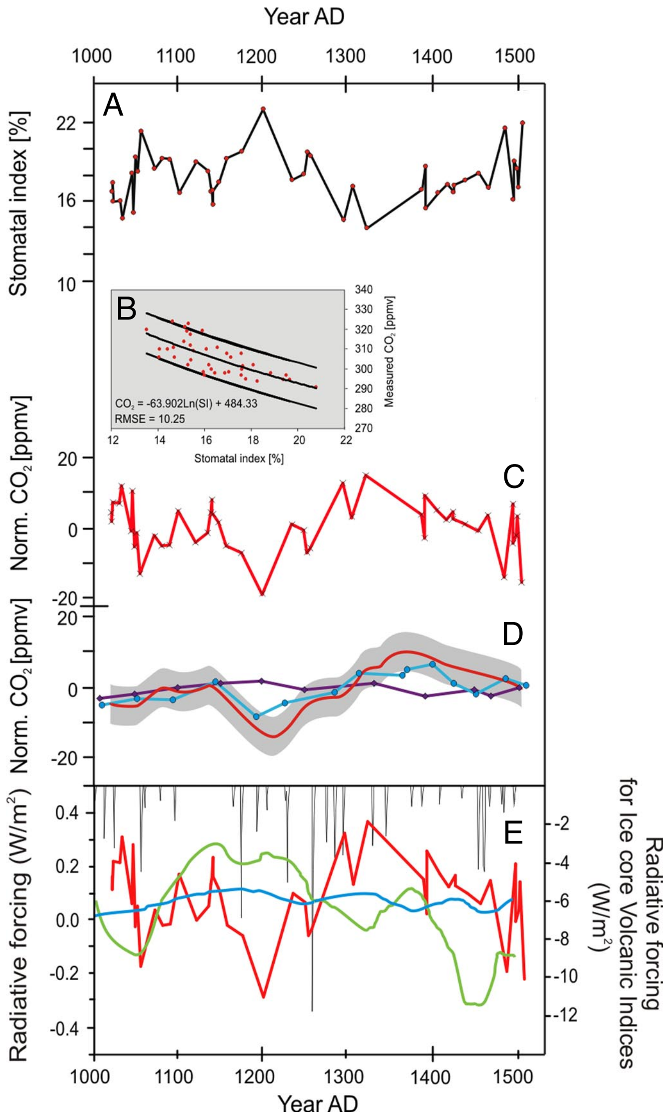

Fig. 1. The CO_2 (SI) record reconstructed for the period A.D. 1000–1500 is compared with Antarctic ice core records and the calculated radiative forcing of this new CO_2 curve is compared with conventional climate forcing factors of the past millennium. (*A*) Stomatal indices of subfossil oak leaves (*Q. robur*) derived from accelerator mass spectrometry ^{14}C wiggle-match dated oxbow-lake deposits from the Netherlands (30). (*B*) SI–CO_2 inference model developed for *Q. robur* based on leaves from herbaria and subrecent peat deposits (22). (*C*) SI-based normalized atmospheric CO_2 fluctuations for the period A.D. 1000–1500. (*D*) Comparison between normalized atmospheric CO_2 reconstructions based on ice core data [light blue line: D47, Antarctica (9); purple line: Law Dome, Antarctica (10)] and the normalized CO_2 (SI) data (*C*) smoothed analogously to the natural CO_2 smoothing in the firn of D47 (red line; gray area represents the methodological error; for details see ref. 32). (*E*) CO_2 (SI) radiative forcing (red line) calculated from the normalized SI-based atmospheric CO_2 curve (*C*) compared with other radiative forcing factors (15–17); CO_2 radiative forcing based on ice core data (blue line), solar forcing (green line), and volcanic forcing (black lines).

Although some of the preindustrial CO_2 changes are at least temporally associated with anthropogenic influences on the environment, the amount of carbon needed to cause a shift of 34 ppmv would far exceed the size of potential carbon sources and

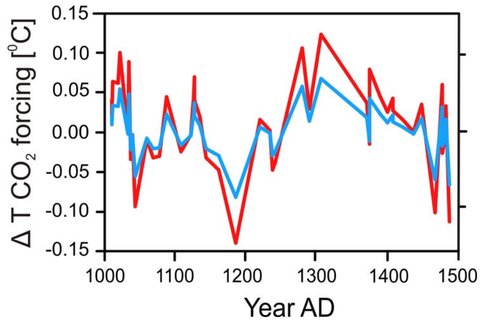

Fig. 2. Estimated global temperature effects on the SI-based CO_2 forcing calculated with a low (blue line) and high (red line) sensitivity mode of the ECBILT-CLIO coupled atmospheric-ocean-sea ice model (43, 45).

sinks in the terrestrial biosphere. It is likely that, analogous to early Holocene CO_2 changes (25–28), depletion and restoration of atmospheric CO_2 between A.D. 1000 and 1500 was driven mainly by short-term perturbations of sea-surface temperature and/or salinity. Similar to the CO_2 trend based on *Tsuga heterophylla* needles (29), within the dating uncertainties, the present stomata-based CO_2 reconstruction correlates to a large extent with proxy sea-surface temperature records from various parts of the North Atlantic Ocean (36–38).

Concluding Remarks

A coherent scenario explaining preindustrial atmospheric CO_2 changes of the last millennium and their possible temporal link with changes in terrestrial and marine carbon uptake or release still needs to be established. Reconstructed multidecadal changes are not as prominent as man-made CO_2 increases since the onset of industrialization. Yet it seems obvious that a dynamic CO_2 regime with fluctuations of up to 34 ppmv implies that CO_2 can no longer be discarded as a forcing factor of preindustrial air-temperature changes. The results of our study therefore underscore the need to understand anthropogenic global warming within the context of rates and amplitudes of natural CO_2 variability of the last millennium. A stomata-based CO_2 record may provide an important observational constraint on the sensitivity of climate models.

Materials and Methods

We based our study on a series of CO_2 estimates derived from well preserved *Q. robur* leaf remains, which occur continually in the organic-rich infill of an oxbow lake of the river Roer near the village of Sint Odiliënberg, Province of Limburg, southeastern part of the Netherlands (51.088 N 6.008 E; for details see ref. 30). The studied leaf record was derived from 60 successive horizons, which were accurately dated by accelerator mass spectrometry ^{14}C wiggle-match dating (for details see ref. 30).

Because of significant differences between the stomatal frequency in sun and shade leaves of *Quercus*, we restricted the analysis to sun morphotypes. Standardized stomatal frequency counts were made by using the image-analysis program analySIS 3.0 (Soft Imaging System) on the digitized images. Parameters measured were (mean) epidermal cell density (ED; number per mm^2) and (mean) stomatal density (SD; number per mm^2). To evade influences of lateral epidermal cell expansion resulting from contrasting light regimes, leaf age, or water availability (39, 40) from SD and ED, the area-independent (mean) SI (41) was calculated as

$$SI[\%] = [SD/(SD + ED)] \cdot 100. \qquad [1]$$

Calculated SI values (Fig. 1*A*) are mean values for five leaves per sampling point. Seven images per leaf with a field area of 0.03 mm^2 were analyzed (standard deviations are constant after seven counts). SI values were transferred into CO_2 mixing ratios (Fig. 1*C*) by means of an inference model based on the species-specific stomatal frequency adjustment to the historical atmospheric CO_2 increase of the last ≈150 years. For this model (Fig. 1*B*), SI values of accurately dated *Q. robur* leaves from Dutch herbaria and young peat deposits were compared with the global atmospheric CO_2 trends recognized at Mauna Loa and in shallow Antarctic ice cores (for details see ref. (23), resulting in the following inference model:

$$CO_2[ppmv] = -63.902 \ln(SI) + 484.33. \qquad [2]$$

To calculate the strength of radiative forcing induced by the CO_2 changes observed in the Dutch stomatal frequency study, we followed the approach of Myhre *et al.* (42), who expressed the radiative forcing as:

$$dF[W/m^2] = \alpha \cdot \ln(C/CO) + \beta \cdot (\sqrt{C} + \sqrt{CO}), \qquad [3]$$

where *dF* represents the radiative forcing, *C* represents the CO_2 mixing ratio, *CO* represents the unperturbed mixing ratio, $\alpha = 5.35$, and $\beta = 0.0906$.

IPCC arbitrarily takes A.D. 1750 as the preindustrial baseline (43). Therefore, to identify changes in radiative forcing induced by the reconstructed CO_2 changes, normalized stomata-derived CO_2 data were superimposed on the corresponding CO_2 reference level of 278 ppmv. It should be noted that, in general, CO_2 data derived from stomatal frequency analysis have higher average values (≈300 ppmv) compared with the IPCC baseline (21, 25–28). Effects of the changes on global air temperatures were estimated with the ECBILT-CLIO coupled atmosphere–ocean–sea ice model (44, 45).

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