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The Potential Role of Peatland Dynamics in Ice-Age Initiation

LEE F. KLINGER
The National Center for Atmospheric Research, P.O. Box 3000, Boulder, Colorado 80307

JOHN A. TAYLOR
Centre for Resource and Environmental Studies, The Australian National University, Canberra, ACT 0200, Australia

AND

LARS G. FRANZEN
Department of Physical Geography, Göteborg University, Reutersgatan 2C, S-413 20 Gothenburg, Sweden

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Physical and chemical coupling of peatland vegetation, soils and landforms, and atmosphere creates feedbacks which may be important in ice-age initiation. A box diffusion CO_2 exchange model shows that a transient forcing of 500 Gt C (the amount proposed to have accumulated in peatlands during the last interglacial–glacial transition) over 5000 yr results in a lowering of atmospheric CO_2 by about 40 ppm. Proxy data indicate that a decrease in atmospheric CO_2 may have occurred over the last 5000 yr up to preindustrial times, and the amount is similar to that calculated from Holocene peatland expansion (~22 ppm). These results suggest that models should consider the role of peatlands in ice-age initiation.

INTRODUCTION

Recent work on carbon and water dynamics in peatlands has led some investigators to postulate climate regulation mechanisms involving the effects of peatland growth on decreased atmospheric CO_2 and thus possibly the radiative cooling of the atmosphere. Both Klinger (1991) and Franzen (1994) have independently developed models of peatland dynamics during a glacial–interglacial cycle that may account for carbon dioxide values and atmospheric temperatures derived from ice cores (Barnola *et al.,* 1987). Focusing on landscape–atmosphere feedbacks involving ecological processes, Klinger (1991) proposed that the radiative cooling due to decreased atmospheric CO_2, increased surface albedo, and increased cloud cover associated with large-scale change from forest to peatland in both temperate and tropical regions plays an important role in the initiation and maintenance of ice-age climates. Large-scale shifts from forest to peatlands are primarily due to succession processes occurring over millennial timescales under low-disturbance regimes (Klinger, 1990, 1996; Klinger *et al.,* 1990, 1994; Klinger and Short, 1996). Franzen (1994) proposed that ice-age cycles are generated by radiative cooling due to decreased CO_2 and CH_4 resulting from peatland growth and subsequent burial under ice sheets in temperate regions. His hypothesis emphasizes landscape–atmosphere feedbacks involving geomorphological processes, i.e., glaciers create landforms favorable for peatland formation following deglaciation. Although differing in certain details, these two hypotheses, when taken together, suggest that the physical and chemical coupling of peatland vegetation, soils, landforms, and atmosphere creates feedbacks that may be important in ice-age initiation.

The critical role of atmospheric CO_2 in affecting the radiation balance of the atmosphere is clearly known. Whether decreases in atmospheric CO_2 are a driving force in ice-age cooling is less clear. However, the correlation between atmospheric CO_2 and temperature over the last glacial–interglacial cycle is significant enough to imply that the two phenomena are closely coupled (Genthon *et al.,* 1987; Saltzman and Verbitsky, 1994; Franzen, 1994). Many authors have proposed that increased oceanic uptake of CO_2 due to higher primary productivity and/or increased alkalinity under glacial climates is primarily responsible for the lowered atmospheric CO_2 observed in ice cores (e.g., Sarmiento and Toggweiler, 1984; Boyle 1990; Broecker and Peng, 1993; Struck *et al.,* 1993). However, several authors have found evidence that oceanic uptake and storage of carbon may not be sufficient to explain the CO_2 dynamics associated with the last interglacial–glacial–interglacial cycle (Crowley, 1991; Pedersen *et al.,* 1991; Mortlock *et al.,* 1991). Ultimately, any global hypothesis regarding interglacial–glacial carbon dynamics should involve both oceanic and terrestrial mechanisms.

This paper focuses on the role of carbon accumulation in peatlands in lowering the concentration of CO_2 in the atmosphere. The objective is to determine whether carbon models and proxy data for atmospheric CO_2 are consistent with the hypothesis that carbon accumulation in peatlands lowers atmospheric CO_2, thus playing an important role in ice-age initiation.

BOX DIFFUSION CO_2 EXCHANGE MODEL

Evidence from CO_2 in ice cores indicates that the strongest shift in temperatures from the last interglacial (~120,000 yr B.P.) to glacial (~115,000 yr B.P.) occurred in association with a decrease in atmospheric CO_2 concentration of approximately 40 to 70 ppm (Barnola *et al.,* 1987). Klinger (1991)

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estimated that 500 Gt (1 Gt = 10^{15}g) of carbon accumulated in mid- to high-latitude peatlands during this interglacial–glacial transition. Although there is as much as a factor of two uncertainty in this number, it is supported in the estimate by Crowley (1991) that 450 Gt of carbon occupied the land areas (mostly peatlands) which were subsequently glaciated during the last glaciation. Using a box diffusion CO_2 exchange model (Siegenthaler and Oeschger, 1978), changes in carbon storage in the mixed layer ocean, the deep ocean, and the atmosphere over a 5000-yr period were calculated based on a linear forcing of carbon storage in peatlands from 0 to 500 Gt C over the same time period. The results (Fig. 1a–1d) indicate that most of the carbon stored in peats is compensated for by a decrease in deep ocean carbon (Fig. 1d), but that decreases in carbon pools in the oceanic mixed layer (Fig. 1c) and the atmosphere (Fig. 1b) also occur. Atmospheric carbon, expressed as ppm CO_2, shows a decrease of about 40 ppm over the 5000-yr model run (Fig. 1b). This finding is consistent with the hypothesis that carbon accumulation in peatlands can account for reductions in atmospheric CO_2 at a magnitude consistent with the reduction observed during ice-age initiation.

EFFECTS OF LATE HOLOCENE PEATLAND EXPANSION ON ATMOSPHERIC CO_2

The late Holocene has seen a dramatic increase in the global extent of peatlands. Although this increase is not as large as that postulated to occur during an interglacial–glacial transition, it is perhaps great enough to affect atmospheric CO_2 significantly. Using conservative assumptions, estimates can be made of the approximate amount of carbon stored in peatlands during the late Holocene. The estimated increase in peatland area over the past 5000 yr is 3 × 10^6 km^2 (Neustadt, 1982; Klinger, 1991). Assuming that (i) the vast majority of late Holocene peatlands have formed at the expense of boreal forest, (ii) carbon storage in boreal forest is 15 kg C per m^{-2}, and (iii) carbon storage in peatlands (average depth 2.3 m) is 112 kg C per m^{-2} (Gorham, 1991), then the net increase in carbon storage due to peatland formation is 291 Gt C. Applying this value to the box diffusion CO_2 exchange model (Siegenthaler and Oeschger, 1978) results in a net decrease in atmospheric CO_2 of 22 ppm.

Given that there have been no changes of similar magnitude reported for other carbon pools during the late Holocene (excluding the last 150 yr), the above-modeled changes in atmospheric CO_2 may be observable in the proxy CO_2 record. Proxy data for atmospheric CO_2 in the late Holocene have not been previously examined for trends. Proxy atmospheric CO_2 from seven data sets spanning the late Holocene are separated into longer time scale records (Fig. 2a) and shorter timescale records (Fig. 2b). All the data are derived from ice cores except for Stuiver *et al.* (1984), who inferred atmospheric CO_2 from stable carbon isotopes in tree rings, and White *et al.* (1994),

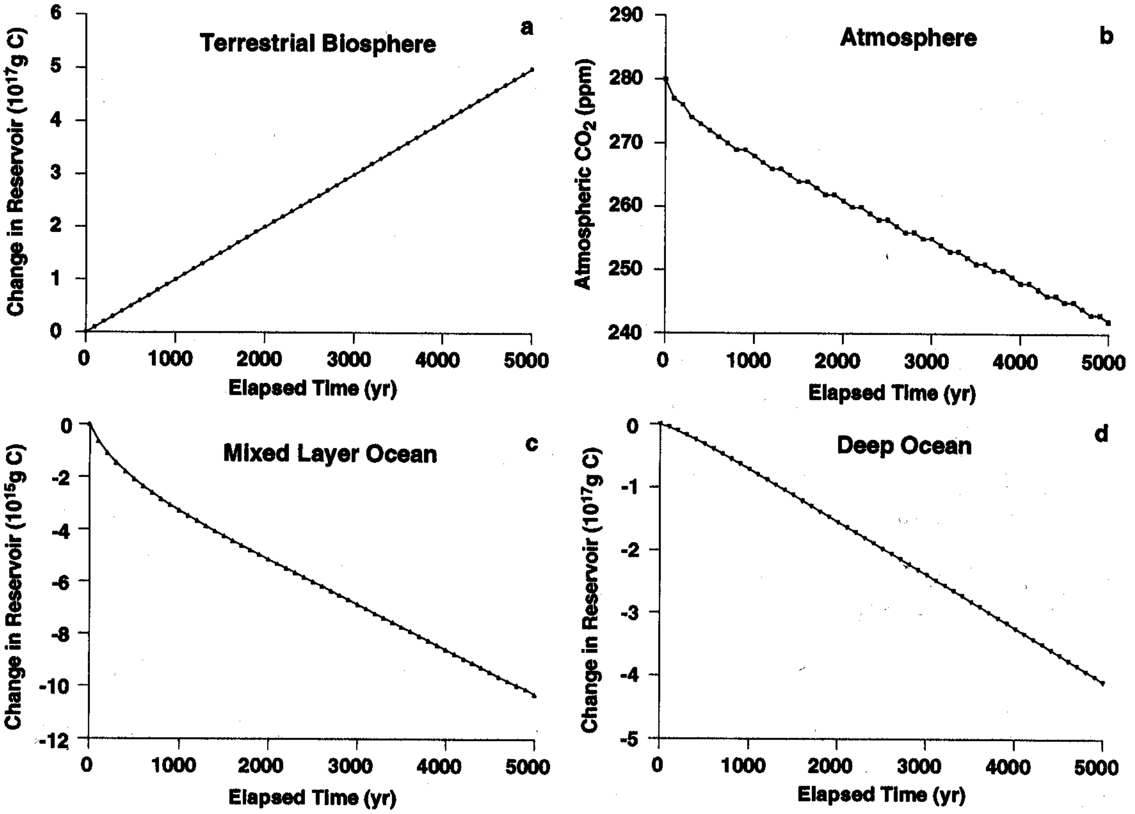

FIG. 1. Box diffusion CO_2 exchange model (Siegenthaler and Oeschger, 1978) results for a transient forcing of 500 Gt C accumulation (in peatlands) over 5000 yr in the terrestrial biosphere (a), showing the response of carbon pools in the atmosphere (b), mixed layer ocean (c), and the deep ocean (d).

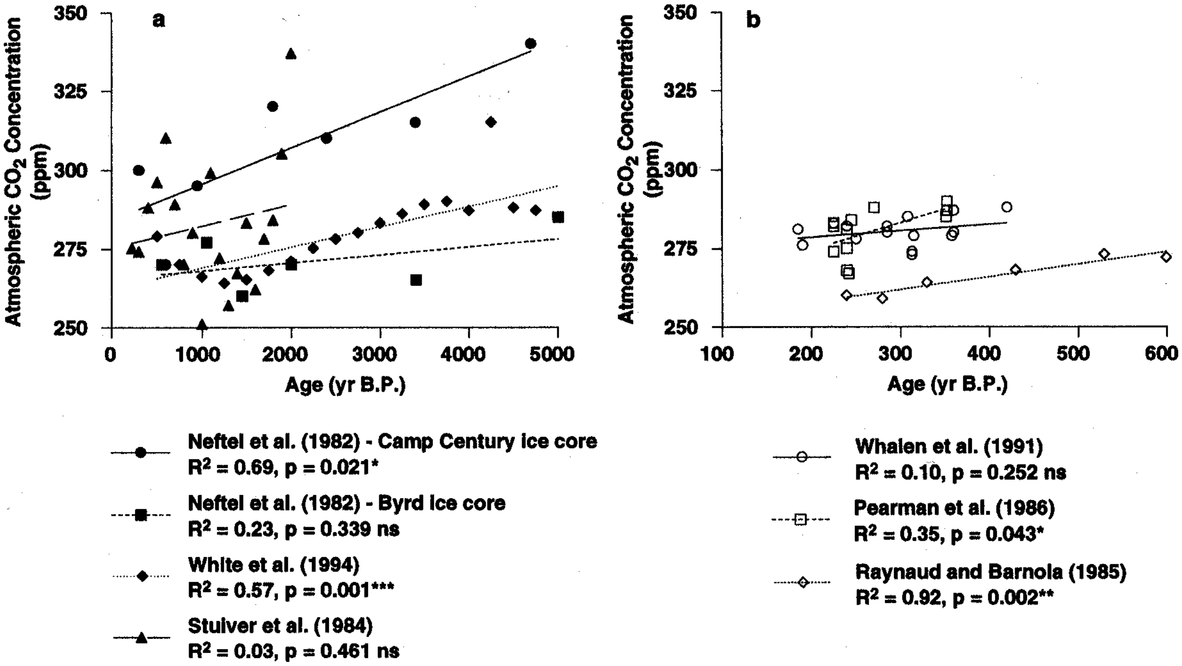

FIG. 2. Published proxy data for atmospheric CO_2 during the late Holocene for long timescale records (a) and recent short timescale records (b). Lines depict best fit linear regressions.

who derived past CO_2 concentrations from stable carbon isotopes in peat deposits. In the Neftel *et al.* (1982) data sets, outliers that were identified as possibly being contaminated and that exhibited very large error bars were excluded (two data points from each set).

Linear best fits indicate that all the data sets exhibit a decreasing trend in CO_2 concentration during the late Holocene which has not been previously reported. However, as the R^2 and probability values indicate, only four of the seven data sets show a statistically significant trend. In addition, each of these data sets have errors and uncertainties associated with them that are not reflected in these regressions. Therefore, these results should be viewed with caution.

For the long timescale records (Fig. 2a), linear equations used to calculate the rates of the CO_2 concentration change during the late Holocene (0 to 5000 yr B.P.) show decreases of 0.011 ppm·yr^{-1} (Camp Century core; Neftel *et al.*, 1982), 0.003 ppm·yr^{-1} (Byrd core; Neftel *et al.*, 1982), 0.007 ppm·yr^{-1} (Stuiver *et al.*, 1984), and 0.007 ppm·yr^{-1} (White *et al.*, 1994). These results are consistent with the proposal that, within the uncertainty of the data, CO_2 concentration decreases can be largely accounted for by Holocene peatland expansion. The rates of the CO_2 concentration decrease during the late Holocene (0 to 5000 yr B.P.) calculated for the short timescale records (Fig. 2b) are 0.086 ppm·yr^{-1} (Pearman *et al.*, 1986), 0.040 ppm·yr^{-1} (Raynuad and Barnola, 1985), and 0.020 ppm·yr^{-1} (Whalen *et al.*, 1991). These rates suggest that atmospheric CO_2 may have decreased faster during the period 150 to 600 yr B.P. than previously in the late Holocene. This observation is consistent with the fact that as peatlands expand, the rate of carbon storage increases. A gradual decrease in global temperature during the late Holocene, as determined from ice cores and tree rings (Feng and Epstein, 1994), is consistent with the trends reported here and the hypothesized role of decreasing CO_2 in ice-age initiation, although other mechanisms such as decreased insolation may also be involved.

DISCUSSION AND CONCLUSIONS

Considering the huge reserves of organic carbon in peatlands, any hypothesis that postulates shifts in carbon storage to explain atmospheric CO_2 trends during a glacial–interglacial cycle must include peatland dynamics. The potential for peatlands to affect the carbon balance of the atmosphere has been recognized previously (Sjörs, 1980; Billings, 1987; Gorham, 1991). Recent estimates of carbon storage in peatlands range from 300 Gt C (Clymo and Hayward, 1982) to 860 Gt C (Bohn, 1976), although most estimates seem to be converging around 450 to 500 Gt C (Gorham, 1991; Botch *et al.*, 1995). Most of this carbon has accumulated during the late Holocene, and, in areas unaffected by human land use, continues to accumulate as peatlands grow and expand. It has been proposed that over the short term, the cool, moist conditions associated with an ice-age climate would tend to favor peatland formation and expansion, thus creating a positive feedback that could induce relatively rapid shifts from interglacial to glacial conditions (Klinger, 1991). It is interesting that the atmospheric CO_2 proxy data presented above hint at an increased rate of atmospheric CO_2 depletion during the late Holocene. Ultimately, ice sheet formation and expansion would limit peatland growth at higher latitudes. Whether extensive peatland formation at lower latitudes occurs during the later stages of an ice-age is still unclear.

The model and empirical results presented here are consistent with, but do not prove, the hypothesis that carbon accumulation in peatlands plays an important role in ice-age initiation through a lowering of atmospheric CO_2. Shifts in other carbon pools, particularly oceanic carbon uptake, as well as earth orbital forcing (Imbrie *et al.,* 1992) are also likely to be involved in ice-age initiation. Peatland formation, as well as other types of large-scale landscape changes may also affect the radiation balance of the atmosphere by altering surface albedo (Klinger, 1991; Bonan *et al.,* 1992) and cloud cover (Klinger, 1991). Therefore, a new model that accounts for both oceanic and landscape (especially peatland) change in the context of earth orbital forcing may be needed to explain ice-age initiation adequately.

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