Multivariate Climate Reconstruction for the Last 14,000 Years in Southernmost South America

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ABSTRACT: Comparison between past changes in pollen assemblages and stable isotope ratios (deuterium and carbon) analyzed in the same peat core from Tierra del Fuego at latitude 55°S permitted identification of the relative contribution of precipitation versus temperature responsible for the respective change. Major steps in the sequence of paleoenvironmental changes, such as at 12700, 9000, 5000, and 4000 years ago are apparently related only to increase in precipitation, reflecting the latitudinal location and intensity of the westerly storm tracks. On the other hand, high paleoenvironmental variability, which is characteristic for the late-glacial and the latest Holocene, is related to temperature variability, which affects the relative moisture content. Comparison with other paleoenvironmental records suggests that the late-glacial temperature variability is probably related to variability in the extent of Antarctic sea-ice, which in turn appears to be related to the intensity of Atlantic deep-water circulation. Temperature variability during the latest Holocene, on the other hand, is probably related to the dynamics of the El Niño/Southern Oscillation.

Introduction

Late Pleistocene paleoclimate patterns for southern South America are reconstructed from pollen records analyzed from lake and bog sediments recovered between latitudes 40° and 55°S from both sides of the Andes (Markgraf 1991a, 1993a; Villagran 1990, 1993; Heusser 1984; Lumley and Switsur 1993; Ashworth *et al* 1991). Modern environments in this latitudinal band range from warm- to cool-temperate mixed evergreen rain forest to deciduous forest, moorland, steppe and heath, and Andean fjellfield. These major vegetation types reflect the latitudinal and elevational gradients in seasonal precipitation and temperature as well as the rain-shadow effect of the Andes. Cool-temperate rain forests and moorland vegetation on the west coast of southern Chile, for example, receive between 3000 and 5000 millimeters mean annual precipitation, whereas the steppe-forest limit east of the Andes receives less than 600 millimeters. Toward the northern limit of the temperate forests, precipitation occurs primarily in winter; at higher latitudes, precipitation is either aseasonal or has a summer maximum. Seasonality of precipitation is related to the seasonal latitudinal shift of the westerly storm tracks, poleward in summer and equatorward in winter.

This semi-quantitative relationship between vegetation types and climate parameters is the primary source for paleoclimatic interpretation of past changes in vegetation types reconstructed from pollen assemblage changes (Markgraf 1993a). When developing high-resolution paleoclimate histories, however, the lack of a quantitative climate calibration

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of pollen assemblages is a handicap (Markgraf 1991b, 1993b). Most critically needed in the attempt to enhance paleoclimate inferences is the ability to quantitatively distinguish between precipitation and temperature parameters. The only earlier pollen/climate transfer function attempt for southern Chile (Heusser and Streeter 1980) yielded unrealistic results, suggesting that the calibration dataset was not adequate. More promising are recent advances using pollen/climate response surface analysis (Anderson and Markgraf 1993). Regression of a spatial network of climate parameters and modern pollen types allows definition of every pollen taxon's climate space, information that can then be used to translate down-core pollen taxa abundances in quantitative climate terms. Ultimately, however, every climate/pollen calibration approach for southern South America will be limited by the limited climate data available.

Another approach to enhance paleoclimatic interpretation is a multi proxy-climate indicator analysis. Recent advances in quantitative paleoclimate interpretation using stable isotopes on organic materials led us to pursue a combined study, analyzing on the same peat core samples pollen, carbon, and deuterium isotopes.

Methods

The core chosen for this multivariate paleoclimate study was recovered from a raised *Sphagnum* peat bog near Estancia Harberton, in the eastern Beagle Channel in Tierra del Fuego, about 50 kilometers east of Ushuaia (latitude 55°S, longitude 67°W). The moss and sedge components of the 10-meter-long peat core are very well preserved. Interpolation between 21 radiocarbon dates (with a basal date of 13600 YBP) suggests a uniform growth rate of 1 centimeter per 15 years. An exception is the interval between 9000 and 10000 (11000) YBP, when fires apparently burnt the bog surface and temporarily changed growth conditions and hence growth rates (Markgraf 1991b, 1993b).

Results

Major times of change according to pollen assemblage changes (Figure 1) date to 12500 YBP when *Empetrum* (Ericaceae) heath was replaced by steppe, to 9000 YBP when *Nothofagus* woodland replaced the steppe, and to 4000 YBP when, after a 1000-year-long heath re-expansion, modern dense *Nothofagus* forests developed.

Results of the carbon isotope analyses on the moss components (*Sphagnum* spp. and *Drepanocladus* s.l.) have been interpreted to reflect changes in the atmospheric content of carbon dioxide (White *et al* 1994; Figge *et al* in press). Three high-amplitude peaks (Figure 1) in the carbon isotope ratios, at 12900, 11600, and 10200 YBP, suggest that there were marked past "pulses" in atmospheric carbon dioxide, which probably

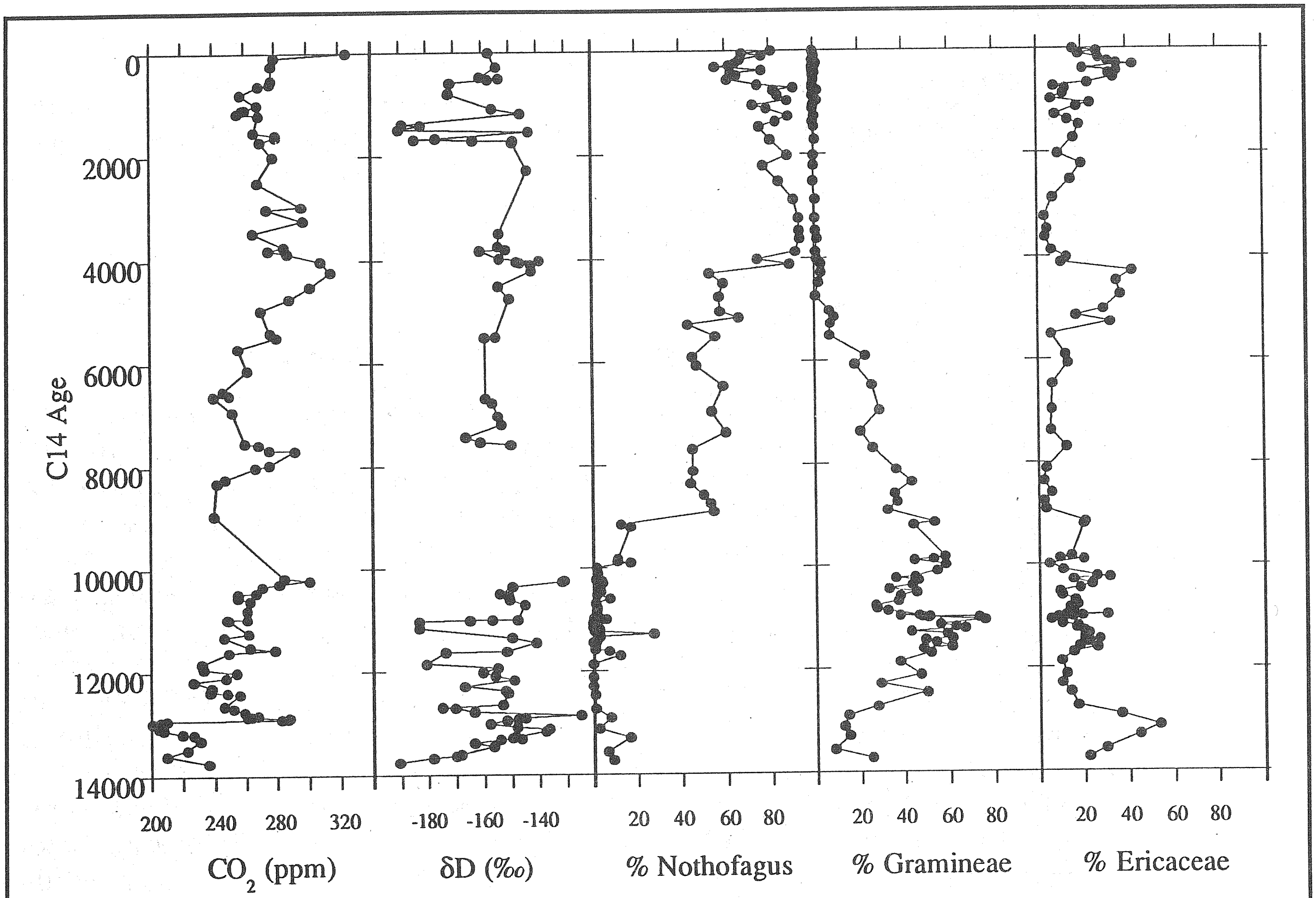

Figure 1. HARBERTON PEAT CORE SHOWING THE LAST 14000 YEARS OF CHANGE IN ATMOSPHERIC CO2 (ANALYZED FROM $\delta^{13}C/^{12}C$ RATIOS IN MOSSES), δD, AND THREE OF THE MAJOR POLEN TAXA: *NOTHOFAGUS* (SOUTHERN BEECH), GRAMINEAE (GRASSES), AND *EMPETRUM* (HEATH).

relate to intervals of deep-ocean degassing events, which in turn relate to changes in intensity of deep-water circulation (Figge and White submitted). Less-rapid and lower-amplitude changes in carbon dioxide also occurred during the Holocene; however, they do not seem related to changes in the thermohaline circulation.

Results from the deuterium analyses are the focus of the following discussion. Ratios between D/H of local precipitation reflect temperature at the site of precipitation (lower temperatures result in more depleted δD values; Dansgaard 1964). δD values of non-exchangeable (C-bound) hydrogen in plant cellulose reflect the δD values of environmental water used by the plant during growth (Epstein *et al* 1976). Thus, δD values from ancient, well-preserved cellulose may provide paleoclimatic information. We have found that the δD values of environmental water in southern South America is indeed strongly controlled by temperature, yielding a δD/temperature gradient of 4‰/°C (White and Kenny in prep).

Several pre-treatment techniques (Brenninkmeijer 1983; White 1983; Coleman *et al* 1982) were tested for efficiency to remove exchangeable hydrogens from the moss cellulose and hemicellulose; especially the oxygen-bound hydrogens (hydroxyls) are readily exchangeable (Epstein *et al* 1976) and, therefore, need to be removed to obtain a meaningful climate signal. Replicability tests applying different techniques suggest that nitrification procedures proposed by Brenninkmeijer (1983), followed by heating to 200°C under high vacuum, yielded the best results without requiring too much material, which would decrease the temporal resolution of the analyses. The same 1-centimeter samples analyzed for pollen and carbon isotopes were analyzed for deuterium to allow point-by-point correlation between the different paleoclimatic indicators.

The deuterium values in the Harberton record (Figure 1) range from −190 to −130‰, corresponding to a temperature amplitude of more than 10°C. From a value at the base of the record at 14000 YBP of −190‰, deuterium increased rapidly, reaching and exceeding Holocene values of −150‰ between 13500 and 12700 YBP. For the remainder of the late-glacial, variability of the deuterium values is high; values shifted repeatedly and rapidly between −150 and −180‰, which corresponds to temperature shifts of about 3 to 4°C. The duration, especially of the cold intervals, is about 50 years at 12600 YBP, and about 200 years after 11800 YBP, and after 11200 YBP. After a gap related to scarcity of mosses in the sediment, deuterium levels remained relatively stable at −150‰ from 8000 to 4500 YBP. Between 4500 and 4000 YBP, deuterium reached −140‰, representing the relatively warmest temperatures of the Holocene, before returning to early Holocene levels. After 2000 YBP, deuterium variability again increased markedly. Within an interval of 50 years, values jumped from −150 to −190‰, comparable to shifts found during the late-glacial. Using the modern temperature calibration, this implies a temperature decrease of more than 4°C between 2000 and 1700 YBP and between 1000 and 800 YBP.

Comparing changes in the down-core deuterium ratios and pollen assemblages, the former is interpreted to reflect changes in temperature, and the latter interpreted as responding to a combination of temperature and precipitation change, revealing a markedly similar history. Both indicators record high variability during the late-glacial and the latest Holocene and relatively stable climate conditions during the early Holocene. Both indicators follow the same overall pattern of change, and there are no temporal leads or lags between the high amplitude deuterium fluctuations and the proportional shifts of pollen taxa. During the late-glacial, varying proportions of *Empetrum*, Gramineae, and herbaceous taxa represent different types of the late-glacial treeless vegetation in high southern latitudes. During the Holocene, *Nothofagus* enters into the proportional game. This synchroneity of change of the different indicators suggests that either temperature is the leading cause of environmental change in the high southern latitudes or that temperature changes are linked to precipitation changes. A more detailed comparison of deuterium ratios and pollen assemblage changes may help determine which is the case.

The initial rapid deuterium increase culminating between 13500 and 12800 YBP was accompanied by replacement of a species-rich herbaceous steppe pollen assemblage by a depauperate, arid *Empetrum* heath assemblage (Markgraf 1993b). These changes imply that the temperature increase was not compensated by a precipitation increase. The return of Holocene-level deuterium values, which followed a strong but brief interval of more negative values at 12600 YBP, was synchronous with a replacement of *Empetrum* heath by a Gramineae-dominated herbaceous steppe, with substantial amounts of Cyperaceae. This suggests that the temperature increase that followed the brief cold episode must have been accompanied by at least a modest and seasonally evenly distributed precipitation increase, which markedly increased effective moisture. This condition lasted until 11600 YBP, when deuterium values returned again to more negative levels, suggesting another cooling episode. Gramineae apparently responded to the cooling with a slight decrease due to an increase in herbaceous taxa. With the subsequent temperature increase, herbaceous taxa decreased strongly, whereas both *Empetrum* and Gramineae increased. The return of *Empetrum* implies that at that time effective moisture decreased again, probably because precipitation decreased, especially during the warm season. During the final late-glacial cooling episode at 11000 YBP, *Empetrum* decreased and Gramineae increased. This is perhaps best explained in terms of greater moisture availability under cooler conditions. The abrupt, marked decline in Gramineae shortly after that date again occurred at a time of dramatic temperature increase. At the same levels in the core, charcoal amounts increase substantially, and even the bog surface must have burnt, judging from carbonized moss plants (Markgraf 1993b). Thus, the decline in Gramineae is linked indirectly to increased fire frequency as it relates to soil instability as suggested by high levels of herbaceous disturbance indicators, such as ferns, *Gunnera, Acaena, Plantago, etc.*

During the transition interval from late-glacial steppe and steppe/heath vegetation to *Nothofagus* woodland between 10000 and 9000 YBP, mosses are too scarce for deuterium analyses. Continuing high charcoal amounts in the core suggest that fires continued until about 9000 YBP. The burning altered the bog's nutrient balance, which in turn affected microbial activity, decomposition rates, and preservation of the mosses (Markgraf 1993b).

By 8000 YBP, when well preserved mosses are again present, deuterium values are similar to present values. The regional vegetation, however, is less densely forested than today, suggesting greater moisture stress than today, due probably to lower summer precipitation than today (Markgraf 1991a). Of interest is the mid-Holocene warm period, which culminated (according to the deuterium data) between 4500 and 4000 YBP. The pollen data show a marked increase in *Empetrum* between 5000 and 4000 YBP, which suggests a return to substantially more arid conditions than before. As during the late-glacial, the temperature increase was accompanied by a precipitation decrease, especially during the summer.

The mid-Holocene decrease in precipitation affected all the southern temperate forest region, including the wettest moorland regions in the Chilean Channels (Ashworth *et al* 1991), implying that the westerly storm tracks were located equatorward of their modern position. The onset and termination of this mid-Holocene interval occurred in less than 50 years. With the abrupt ending of the warm period at 4000 YBP, the forest became quite dense, suggesting precipitation increased markedly, especially during the warm season.

High variability for both deuterium and pollen characterizes the last 2000 years. The magnitude and frequency of fluctuations of deuterium ratios and pollen proportions at that time equals the late-glacial fluctuations. Twice within less than 200 years, temperatures fluctuated by more than 4°C, reaching minima unequaled since the late-glacial. Another lesser, but longer, temperature decrease occurred after 1000 YBP, which according to the pollen data did not seem to have had much effect on the regional seasonal precipitation pattern. However, the subsequent abrupt temperature increase did again favor expansion of *Empetrum* and increase in fire frequency, suggesting a return to less equable precipitation.

Discussion

High variability in temperature during the late-glacial and the latest Holocene affects regional vegetation composition primarily by altering the effective moisture and fire regimes. Although the paleoclimatic signature during both intervals of high variability is comparable, causes of the variability are different for both time intervals. Intra- and inter-hemispheric correlation of paleoclimate records suggests that the latest Holocene short-term succession of different climate modes and high climate variability is related to El Niño/Southern Oscillation climate anomalies (McGlone *et al* 1992; Markgraf *et al* 1992). During late-glacial times, on the other hand, ENSO apparently did not operate like today, probably because the western tropical Pacific climates were dominated by extended land areas, which greatly altered the downstream climate modes (McGlone *et al* 1992; Markgraf *et al* 1992). Instead, the repeated temperature reversals between 12700 and 11000 YBP most likely reflect short-term changes in Antarctic sea-ice extent. One mechanism for short-term variation in circum-Antarctic sea-ice extent could be related to varying intensity of Atlantic deep-water circulation, which in turn would alter the inter-hemispheric ocean heat transport. High resolution deep-sea records interpreted to document rapid changes in intensity of Atlantic deep-water circulation (Lehman and Keigwin 1992; Charles and Fairbanks 1992) compare well with temperature fluctuations in the Tierra del Fuego record. This mechanism, then, could synchronize paleoclimate change in both hemispheres and could explain similarity between the deuterium data from the peat core from Tierra del Fuego and the Greenland ice core (White and Kenny in prep.).

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