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Reconstruction of past climates from stable isotope records of palaeo-precipitation preserved in continental archives†

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Abstract The potential of stable isotope ratios ($^{2}H/^{1}H$ and $^{18}O/^{16}O$) of water as a modern tool for palaeoclimatic reconstructions on continents is reviewed. Examples of stable isotope records of palaeo-precipitation preserved in various continental archives (polar ice sheets, mid- and low latitude glaciers, lacustrine deposits, groundwater) are presented, and the methodology of their interpretation in terms of climatic changes is briefly discussed. To interpret quantitatively the isotope records preserved in continental archives, the response of the isotopic composition of precipitation to long-term fluctuations of key climatic parameters (temperature, precipitation amount, relative humidity) over the given area should be known. Further, the transfer functions relating the climate-induced changes of the isotopic composition of precipitation to the isotope record preserved in the given archive should be established. Since the isotopic composition of precipitation has been monitored only for the past three decades, alternatives ways of assessing the long-term climatic sensitivity of the isotopic signature of precipitation are being investigated. The isotope composition of precipitation should be viewed not only as a powerful proxy climatic indicator but also as an additional hydrometeorological parameter which should be explored as a diagnostic tool for the modelling of climate-induced changes in the water cycle, both on a regional and a global scale.

Reconstitution des climats passés à partir de résultats d'isotopes stables des paléo-précipitations conservées dans les archives continentales

Résumé L'article examine le potentiel du contenu en isotopes stables de l'eau ($^{2}H/^{1}H$ et $^{18}O/^{16}O$) en tant qu'instrument moderne pour les reconstitutions paléoclimatiques continentales. Des exemples de teneurs en isotopes stables de paléo-précipitations conservées dans diverses archives continentales (couches de glace polaire, glaciers de moyennes et basses latitudes, dépôts lacustres, eaux souterraines) sont présentées

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et la méthodologie de leurinterprétation en termes de modifications climatiques est brièvement commentée. Afin d'interpréter quantitativement les teneurs en isotopes issues des archives continentales, on devra connaître, pour la zone étudiée, la réponse de la composition isotopique des précipitations aux fluctuations à long terme des principales variables climatiques (température, hauteur des précipitations, humidité relative). Les fonctions de transfert reliant les modifications de la composition isotopique des précipitations induites par le climat et les valeurs des isotopes issues de l'archive considérée devront également être établies. Etant donné que la composition isotopique des précipitations n'a été enregistrée que depuis une trentaine d'années, d'autres solutions sont envisagées afin d'estimer la sensibilité climatique à long terme de la signature isotopique des précipitations. La teneur en isotopes stables dans les précipitations devrait être considérée non seulement comme un puissant indicateur reflétant les conditions climatiques mais également comme une variable hydrométéorologique par procuration qui devrait être explorée en tant qu'outil de diagnostic pour la modélisation des modifications induites par le climat dans le cycle de l'eau, tant sur un plan régional que planétaire.

INTRODUCTION

The stable isotope ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) in past and present precipitation have become an important tool in the field of global change science. In particular, the results obtained from deep ice cores in Greenland and Antarctica, along with studies of other palaeo-environmental archives, have confirmed the potential of these natural tracers for reconstructing past climates with improved resolution and reliability.

Precise determinations of stable isotope ratios in meteoric water performed in the early fifties revealed a large variability in the isotopic composition of precipitation, both in time and space (Dansgaard, 1953; Epstein & Mayeda, 1953; Friedman, 1953; Craig, 1961). Since 1961, the International Atomic Energy Agency (IAEA), in cooperation with the World Meteorological Organization (WMO), has been conducting a worldwide survey of the isotopic composition of monthly precipitation. The programme was launched with the primary objective of collecting systematic data on the isotope content of precipitation on a global scale, characterizing their spatial and temporal variability and, consequently, providing basic isotope data for the use of environmental isotopes in hydrogeological investigations. It quickly became apparent that the collected data are also useful in other water-related fields such as oceanography, hydrometeorology and climatology.

The data gathered during three decades of operation of the global IAEA/WMO network, supplemented by numerous local studies, provide a fairly detailed picture of spatial and temporal variability of the isotopic composition of meteoric waters worldwide. This variability appears to be controlled by numerous, mutually related factors like surface air temperature, relative humidity of the atmosphere, amount of precipitation, latitude, distance from the coast and elevation of the given area above sea level (Dansgaard, 1964; Yurtsever & Gat, 1981; Rozanski *et al.*, 1993). It also became apparent that, like many other atmospheric properties, the isotopic composition of atmospheric water vapour and, consequently, of precipitation exhibits a broad spectrum of temporal variations.

A considerable amount of theoretical and applied work carried out during the past three decades has resulted in a fairly good understanding of the processes

controlling the isotopic evolution of meteoric waters at different levels of the global hydrological cycle.

It has been demonstrated that the spatial and temporal variations of ^{2}H and ^{18}O isotope composition of precipitation have their origin in isotope fractionation effects accompanying evaporation from the ocean and subsequent condensation during the atmospheric transport of water vapour. It has also become apparent that the isotopic composition of local precipitation, in particular at mid- and high latitudes, is controlled by regional-scale processes, i.e. by average parameters of the evaporation process at source regions of atmospheric moisture, and by average water vapour transport patterns into the continents and the resulting "rain-out history" of the air masses precipitating at a given place (Dansgaard, 1964; Craig & Gordon, 1965; Merlivat & Jouzel 1979; Rozanski *et al.*, 1982; Siegenthaler & Matter, 1983; Johnsen *et al.*, 1989).

Quantitative interpretation of isotope records preserved in continental archives requires *a priori* knowledge of the sensitivity of the isotopic composition of precipitation with respect to long-term fluctuations of key climatic parameters (temperature, precipitation amount, relative humidity) over the given area. Unfortunately, the isotopic composition of precipitation has been monitored only for the past three decades. Thus, alternative ways of assessing the long-term climatic sensitivity of the isotopic signature of precipitation are needed.

The link between the isotopic composition of precipitation and climate changes on time scales exceeding instrumental records can be investigated in two ways: (i) through General Circulation Models (GCMs) which simulate the changes in isotopic water cycles ($^{2}H^{1}H^{16}O$, $^{1}H_{2}{}^{18}O$) induced by major climatic shifts (Hoffmann & Heimann, 1993; Joussaume & Jouzel, 1993; Jouzel *et al.*, 1997; and (ii) exploring environmental archives in which variations of $^{2}H/^{1}H$ and $^{18}O/^{16}O$ isotope ratios and of climatic parameters (e.g. temperature) are independently recorded.

Selected examples of isotope records of ancient precipitation retrieved to date from various continental archives are discussed here and a summary of the present understanding of these records in terms of climatic and environmental changes in the past is given.

ISOTOPES IN CONTINENTAL ARCHIVES

There is a rapidly growing amount of isotope data derived from various continental archives (ice cores, lacustrine sediments, corals, groundwater, organic matter, etc.) which can be linked directly or indirectly to the isotopic composition of past precipitation and thus to the evolution of climate. The quality and characteristics of these isotope records such as temporal resolution, representativity for regional/local climate, degree of preservation of isotope signal, vary widely depending on the nature of the given archive and on its geographical setting.

Polar ice sheets

Ice cores offer great potential for studying past climates and other environmental changes because each annual layer deposited on cold glaciers and ice sheets is

assumed to preserve all components that came down with the snow in the year the layer was formed. The isotopic composition of the ice tells about the temperature (Dansgaard 1964; Johnsen *et al.*, 1989; Cuffey *et al.*, 1995; Johnsen *et al.*, 1995a; Jouzel *et al.*, in press), the dust about storminess and source efficiency (Hammer 1977; Steffensen, in press), the air bubbles about the greenhouse gases in the atmosphere (Oeschger *et al.*, 1984; Chappellaz *et al.*, 1993; Raynaud *et al.*, 1993; Bender *et al.*, 1994; Sowers & Bender, 1995), the acidity about volcanic eruptions (Hammer *et al.*, 1980; Clausen *et al.*, 1995), the chemical traces about various processes on land, in the sea and in the atmosphere (Fuhrer *et al.*, 1993; Mayewski *et al.*, 1993; Clausen 1995) at the time of formation of the ice. Together, they give a detailed picture of the environment and climate of the past. All these parameters can be followed in great detail and thus throw light on various facets of the complicated mechanism of climate. Polar ice cores further offer the advantage of recording climate and environmental changes through several glacial cycles.

Six ice cores reaching bedrock have been drilled through the Greenland ice sheet and adjacent smaller ice caps. The first deep core was drilled at Camp Century,

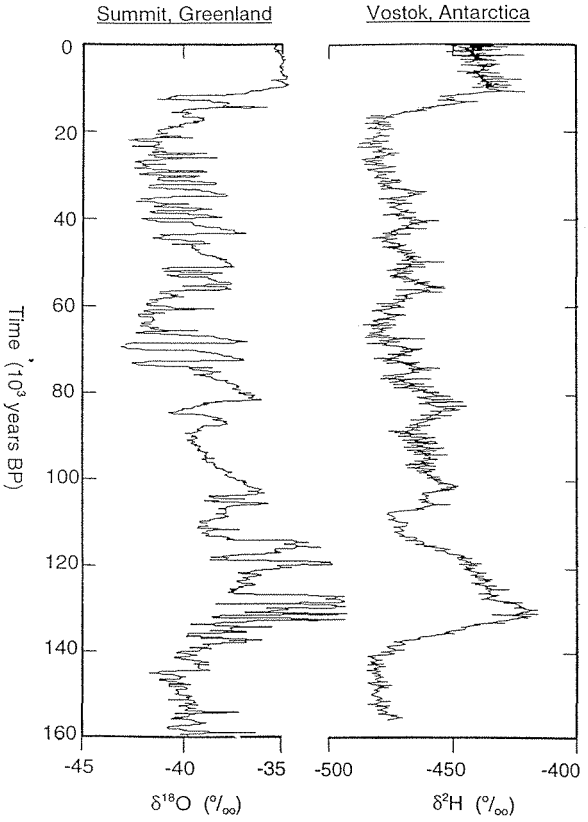

Fig. 1 The continuous $\delta^{18}O$ profile *vs* calculated age, for the GRIP deep ice core drilled on the Summit of the Greenland ice sheet (Dansgaard *et al.*, 1993) and the $\delta^{2}H$ profile *vs* calculated age for the Vostok deep core, East Antarctica (Jouzel *et al.*, 1987a).

northwest Greenland, in 1966 by Ueda & Garfield (1968). It opened up an entirely new era in palaeoclimatology. The $\delta^{18}O$ record demonstrated for the first time the large variability of climate during the last glacial period in Greenland (Dansgaard *et al.*, 1969; Johnsen *et al.*, 1972a). The glacial to interglacial $\delta^{18}O$ shift in the Camp Century core was around 14‰ and the extremely cold glacial period was punctuated by numerous (5–6‰) warm events, the so-called Dansgaard-Oeschger cycles, lasting up to a few thousand years each. This dramatic behaviour was later confirmed by the Dye 3 core in south Greenland (Dansgaard *et al.*, 1982), the Renland core in east Greenland (Johnsen *et al.*, 1992b), and the two newly drilled cores in central Greenland, the GISP 2 (Grootes *et al.*, 1993; Stuiver *et al.*, 1995) and GRIP (Dansgaard *et al.*, 1993; GRIP Project Members, 1993; Johnsen *et al.*, 1992a). Furthermore, several Canadian ice cores have shown a similar stable isotope behaviour (Paterson *et al.*, 1977; Fisher *et al.*, 1995). The largest glacial to interglacial isotope shift (14‰) was found in the Camp Century core and the smallest (4‰) in the Renland core. The central Greenland cores show a 7‰ glacial to interglacial shift in $\delta^{18}O$ while the $\delta^{18}O$ shifts of the warm interstadials in the last glacial range from 4 to 5‰ (Fig. 1). Detailed studies of annual layering in the two Central Greenland cores are used for dating the cores. They show a dramatic reduction (around threefold) of the accumulation rates during the cold glacial stages (Alley *et al.*, 1993; Dahl-Jensen *et al.*, 1993; Dansgaard *et al.*, 1993). The sections of Greenland ice cores corresponding to cold periods are characterized by an elevated dust content (Hammer *et al.*, 1985; Steffensen, in press).

Around 20 years after their discovery, the Dansgaard-Oeschger cycles were identified in other climate proxy records from deep sea sediments (Bond *et al.*, 1993; Keigwin *et al.*, 1994; McManus *et al.*, 1994; Fronval *et al.*, 1995), thus pointing to ocean circulation changes as being the immediate cause for these dramatic climatic oscillations (Dansgaard *et al.*, 1984; Oeschger *et al.*, 1984; Broecker *et al.*, 1985). The deuterium excess (Dansgaard, 1964), which is believed to be related to temperature and humidity in the moisture source area (Merlivat & Jouzel, 1979; Jouzel *et al.*, 1982), has been studied in the Dye 3 core (Johnsen *et al.*, 1989). The values of the deuterium excess were found to be 8‰ for both the present day and the cold glacial conditions, and 4‰ for the relatively warm glacial interstadials between 25 and 37 thousand years BP. The lower deuterium excess value (4‰) in the interstadials was interpreted as being caused by higher relative humidity, with temperatures 2°C colder in the main source regions for the precipitation falling on the Greenland ice sheet. A striking result of the stable isotope study on the Dye 3 core was the identical slope (8.0 ± 0.2) of the meteoric line (δ^2H *vs* $\delta^{18}O$) for all three highly disparate climate regimes, the value also found for present day precipitation at high northern latitudes. The identity of the meteoric line slopes during these periods of totally different climatic environments is believed to indicate that the same absolute water vapour pressure had prevailed in the source regions for high altitude Greenland precipitation (Johnsen *et al.*, 1989). More sophisticated modelling of the global hydrological cycle using GCMs (Jouzel *et al.*, 1987b; Charles *et al.*, 1994) is needed in order to better understand the implications of these findings.

The two sister cores from central Greenland, GRIP and GISP 2, show almost identical climatic histories back to 105 thousand years BP, according to the time scale in Fig. 1. Prior to that time, including the period from 130 to 113 thousand years BP which in the GRIP core has been assigned to the last interglacial or the Eemian period (Dansgaard *et al.*, 1993; GRIP Project Members, 1993), no correlation has been found between the two records, indicating that either one or both of the records are affected by serious stratigraphic disturbances (Grootes *et al.*, 1993). Measurements of CH_4 and $\delta^{18}O$ in atmospheric oxygen of the air trapped in the ice in both the GRIP and the Vostok core suggests strongly that the Eem sequence of the GRIP core is disturbed (Chappellaz *et al.*, in press). This is however at odds with other data from the core that show no sign of foldings and intrusions of alien ice in this section of GRIP core (Johnsen *et al.*, 1995b; Johnsen *et al.*, in press).

The first deep core to bedrock was drilled in Antarctica, at Byrd Station, West Antarctica, in 1968 by the same team that drilled the Camp Century core two years earlier (Ueda *et al.*, 1969). The $\delta^{18}O$ profile (Johnsen *et al.*, 1972b) showed that the core reached almost through the last glacial period. The $\delta^{18}O$ glacial to interglacial shift was found to be around 7‰ and the interstadials in the last glacial were generally smoother and with smaller amplitudes than found in Greenland, indicating a North Atlantic origin for these climatic anomalies. These results were later confirmed by the East Antarctic cores at Dome-Concordia (Lorius *et al.*, 1979) and Vostok (Lorius *et al.*, 1985; Fig. 1), and by the new deep core from Taylor Dome (Grootes *et al.*, in press), which shows more rapid Dansgaard-Oeschger cycles than the other Antarctic cores, more similar to the Greenland results. The deuterium excess in the Vostok core shows lower values in the last glacial period which was assigned to higher relative humidity in the source regions for East Antarctic precipitation (Jouzel *et al.*, 1982). The Vostok core is now the deepest ice core ever drilled (3350 m) and it allows detailed climatic studies of the last four glacial/interglacial cycles in Antarctica (Jouzel *et al.*, 1993; Jouzel, private communication). As in the case of the Greenland ice sheet, the sections of Antarctic ice cores formed during cold periods reveal a high dust load, pointing to a generally much dustier atmosphere (Petit *et al.*, 1990).

Mid- and low latitude glaciers

Cold, high-alpine glaciers located at mid- and low latitudes can be explored as climatic and environmental archives in an analogous way to the large polar ice caps. In particular, they can offer an opportunity to study the mechanisms of climatic coupling between both hemispheres. The question to which extent the climatic changes recorded in ice cores from Greenland and Antarctica are synchronous, could only recently be addressed with an adequate time resolution using the ^{18}O content of atmospheric oxygen trapped in ice (Bender *et al.*, 1994; Sowers & Bender, 1995). Moreover, the low latitude glaciers can be explored as archives preserving the past behaviour of coupled ocean–atmosphere systems such as the ENSO phenomenon or monsoonal oscillations.

During the last few years, several cores have been drilled to the bedrock on ice caps located at mid- and low latitudes and have provided data on the history of the atmosphere chemistry and the temperature of these regions. The interpretation of such data is often more complex when compared with that for polar ice caps, since glaciers located at altitudes between 4000 and 6500 m a.s.l. are influenced by both the planetary boundary layer and the lower troposphere. Other restrictions may be extreme weather conditions or ice thickness, which limits the time resolution of the individual records.

The first ice core records of the glacial/interglacial transition drilled outside of the polar regions were recovered in 1987 from the Dunde Ice Cap located in eastern Tibet (Thompson *et al.*, 1989). The Last Glacial Stage (LGS) ice is characterized by more negative $\delta^{18}O$ values, increased dust content, and decreased soluble aerosol concentrations than in the Holocene sections of the core. A striking feature of the $\delta^{18}O$ record is the enrichment of heavy isotopes toward the present, with the last 50 years characterized as the most enriched period since the end of the LGS (Thompson *et al.*, 1993). The tropical ice core (Fig. 2) recovered from the Huascarán glacier (Peruvian Andes) extends well into the LGS, a time when conditions were much colder, the atmosphere was much dustier, and biological activity in the Amazon Basin to the east was substantially reduced (Thompson *et al.*, 1995). The spatial $\delta^{18}O$–temperature relationship derived for polar regions (see

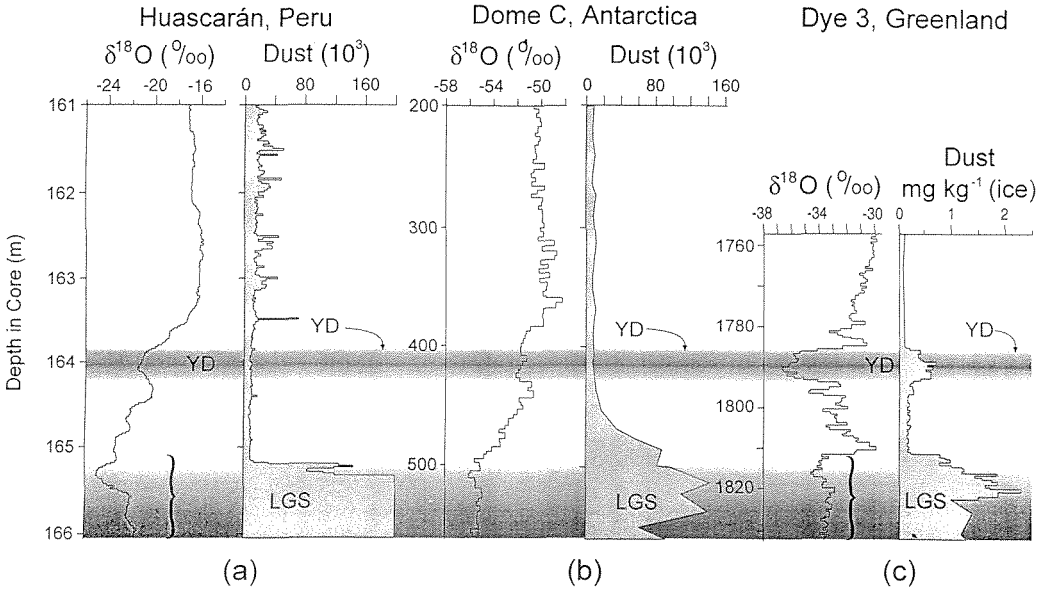

Fig. 2 Comparison of $\delta^{18}O$ and dust records from (a) the Huascarán Glacier (Peruvian Andes); (b) Dome C, Antarctica; and (c) Dye 3, Greenland, for portions containing Last Glacial Stage (LGS) ice, the glacial–interglacial transition with the Younger Dryas cold episode and the Early Holocene. Dust concentrations for Huascarán and Dome C represent the number of particles with diameters between 0.63 and 16 μm ml^{-1} sample. For comparison of the Huascaran and Dye 3 dust records (expressed in mg kg^{-1} of ice): the Huascarán Holocene average is 0.16 mg kg^{-1} and the LGS average is 32.2 mg kg^{-1}.

equation (1) below) when applied to the $\delta^{18}O$ decrease of 8‰ in the LGS ice on Huascaran, suggest that air temperatures may have been lower by as much as 8–12°C at high elevation in the tropics. These temperatures are merely estimates because $\delta^{18}O$ depends on temperatures in the source area of evaporation, the transport history of the air masses, and the air mass mixing. It is clear, however, that the oxygen isotope records in tropical glaciers are also not impacted by variations in sea ice cover during glacial stages. In the polar regions, such changes can increase the distance to moisture sources, which will tend to reduce the $\delta^{18}O$ values in the ice core records during colder climate. Figure 2 illustrates that in spite of the potentially different impacts of these processes at different latitudes, the change of 8‰ between the end of the LGS and the Holocene on Huascarán is comparable with 6‰ at Dome C, Antarctica (Lorius *et al.*, 1979), 7‰ at Dye 3 (Dansgaard *et al.*, 1982) and at Summit, central Greenland (Johnsen *et al.*, 1992a). The tropical ice core data point to a significant drop in temperatures in the tropics during the LGS.

The advantage of European glaciers as climatic and environmental archives is the vicinity to instrumental records as well as to sources of anthropogenic emissions (Schotterer *et al.*, 1985; Wagenbach *et al.*, 1988; Maupetit *et al.*, 1995; Doescher *et al.*, 1997). This allows detailed investigation of the transfer functions and the deposition rates of various physical and chemical constituents, to compare the ice core data with direct measurements and to extend them towards longer time scales. There are several precipitation stations located in the Swiss Alps which have been providing high quality isotope data starting in the early seventies. Both monthly and yearly averages of $\delta^{18}O$ in precipitation reveal reasonably good correlation with ground level temperature up to 2500 m a.s.l. (Siegenthaler & Oeschger, 1980; Rozanski *et al.*, 1993). They can also be directly linked to changes in the isotopic composition of individual components of the regional hydrological cycle such as rivers and groundwater (Schotterer *et al.*, 1993; Schotterer *et al.*, 1995). Figure 3 shows the time series of $\delta^{18}O$ obtained from ice cores drilled in two cold glaciers in the Alps. It illustrates to what extent $\delta^{18}O$ can be used as a proxy indicator of temperature at higher elevations (above 4000 m a.s.l.). On the Colle Gnifetti glacier located at the Swiss–Italian border (4500 m a.s.l.), the annual net accumulation of snow is controlled by wind erosion, which is particularly intensive during winter. The average $\delta^{18}O$ for the period 1910–1978 (–14.5‰) is too high for this altitude and confirms the importance of this process. The seasonal distribution of $\delta^{18}O$ is irregular which makes precise dating of this record very difficult. In the reported example, dating was done by correlating ice lenses within the core with positive summer temperatures at the nearby Grand San Bernard station (Schotterer *et al.*, 1978). Although the correlation of $\delta^{18}O$ with temperature for this core is very poor, some qualitative climatic features such as the warming in the forties are preserved. The glacier is frozen to the bedrock and its lowermost sequence probably contain ice from the last glacial/Holocene transition (Wagenbach, 1994). At the Fiescherhorn plateau (Bernese Alps, 4000 m a.s.l.) the seasonal distribution of accumulated snow is well preserved. The correlation of $\delta^{18}O$ with the temperature record from the nearby Jungfraujoch station is reasonable. The correlation improves if the years with

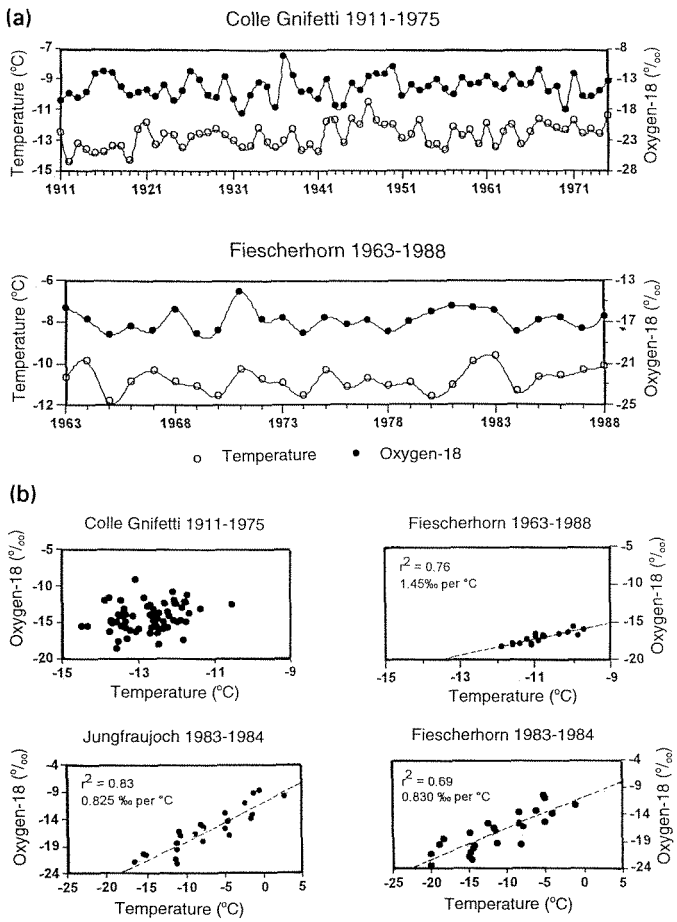

Fig. 3 $\delta^{18}O$ time series from two cold glaciers in the Swiss Alps (Colle Gnifetti and Fiescherhorn), compared with the instrumental record of surface air temperature: (a) $\delta^{18}O$–temperature relationship for long-term changes of both parameters, extracted from the data available for Cole Gnifetti and Fiescherhorn; and (b) the relationship between seasonal changes of $\delta^{18}O$ and surface air temperature for the Jungfraujoch and Fiescherhorn—see text for details.

irregular seasonal distribution of snow deposition are excluded. For the periods of very regular snow deposition, even a monthly comparison with precipitation data is possible (Fig. 3). The apparent increase of both seasonal and long-term $\delta^{18}O$–temperature coefficient with elevation, observed for precipitation and ice core data from the Alpine region in Europe, may have its origin in the generally incomplete preservation of precipitation at high altitudes and/or changes in the seasonality (Schotterer *et al.*, in press).

Lake deposits

Lacustrine deposits are among the most valuable continental materials for palaeoclimatic reconstructions. They can provide high resolution, relatively

continuous records of late Pleistocene/Holocene climatic changes. Lake sediments often contain authigenic carbonates and fossil shells whose oxygen isotope composition is mainly controlled by that of lake water and by temperature. The ^{18}O and ^{2}H isotope composition of open lakes located in mid-latitudes and characterized by relatively fast water turnover responds primarily to changes of the isotopic composition of precipitation over the lake basin, which in turn is temperature dependent. Consequently, the periods of cold and mild climate are reflected by minima and maxima in the ^{18}O content of the deposited calcite. For closed lakes, the isotopic composition of water is largely determined by evaporation and exchange with atmospheric moisture; dry periods, characterized usually by increased evaporation to inflow ratio, are marked by high ^{18}O content. In the tropics, the ^{18}O isotope signature of authigenic calcite deposited in lakes generally reflects the extent of evaporative enrichment of lake water which in turn is connected with the residence time of water in a given lake system and thus reflects predominantly the changes in pluviosity.

Of particular importance for high resolution climatic reconstructions on continents are lacustrine archives which contain annually laminated sediments. Seasonally varying sedimentation patterns in some lakes may lead to the formation of varves which provide a chronological time scale against which different climatic proxies such as pollen, stable isotopes of authigenic carbonates and organic matter can be investigated. However, in most cases such scales are floating. Although they can provide annual resolution for various periods of time, usually they are not fixed on the calendar time scale. Only in rare cases is the absolute calibration of floating chronologies possible, for instance through ^{14}C dating of terrestrial macrofossils preserved in such sediments (e.g. Hajdas *et al.*, 1993; Goslar *et al.*, 1995).

Figure 4 illustrates the potential of laminated lacustrine sediments for high resolution climatic reconstructions. It shows the late Glacial/Holocene transition in central Europe, recorded in the laminated sediments of Lake Gosciaz (central Poland). The ^{18}O content of authigenic carbonates deposited in this lake closely resembles $\delta^{18}O$ variations observed in GRIP and GISP2 ice cores from central Greenland. Within the quoted errors of both chronologies, the transition from Younger Dryas to Preboreal in Greenland and in Europe appears to be synchronous. Figure 4 clearly demonstrates that, under favourable conditions, the lacustrine archives can provide climatic records of comparable resolution with those obtained from ice cores.

The isotopic composition of precipitation in monsoon-controlled regions responds primarily to the amount of rainfall and, consequently, to the intensity of monsoon circulation. Records of the ^{18}O and ^{2}H content of ancient precipitation preserved in various continental archives located in such regions may thus provide important information about the extent and intensity of the major monsoon systems in the past. Figure 5 shows the ^{18}O content of authigenic carbonates deposited during the Holocene in two lakes located on the Tibet Plateau: Lake Siling, located in the central part of the plateau, about 300 km northwest of Lhasa (Morinaga *et al.*, 1993), and Lake Quinghai, located about 1300 km northeast of Lake Siling (Lister *et al.*, 1991) in the northeast corner of the plateau. Lake Siling was under the influence of

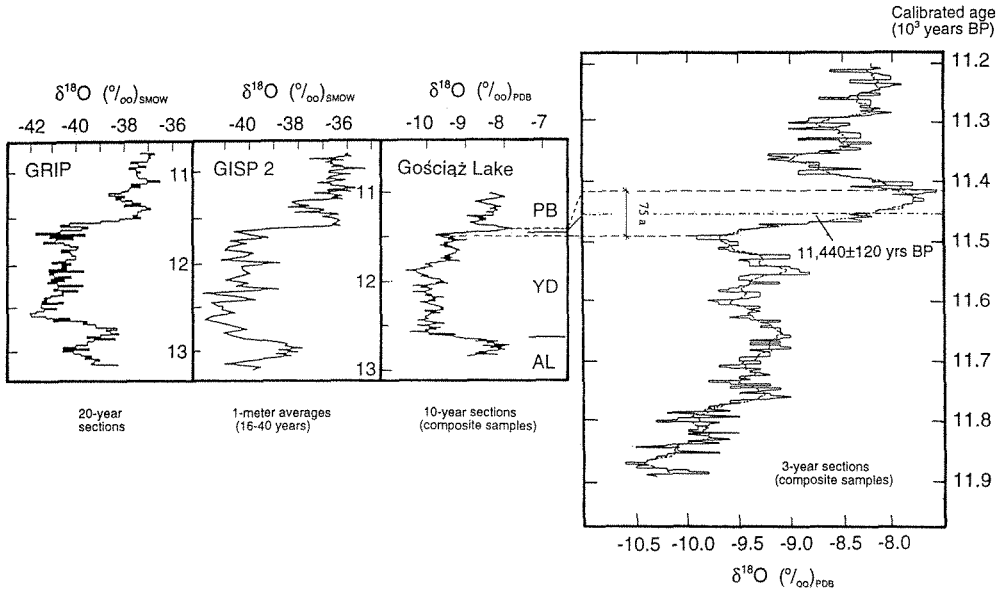

Fig. 4 The Younger Dryas cold episode, as reflected in the $\delta^{18}O$ data of the GISP 2 and GRIP deep ice cores drilled on the Summit of the Greenland ice sheet (Grootes *et al.*, 1993; Johnsen *et al.*, in press) and in the $\delta^{18}O$ of authigenic carbonate deposited in Lake Gosciaz, Central Poland (Goslar *et al.*, 1995).

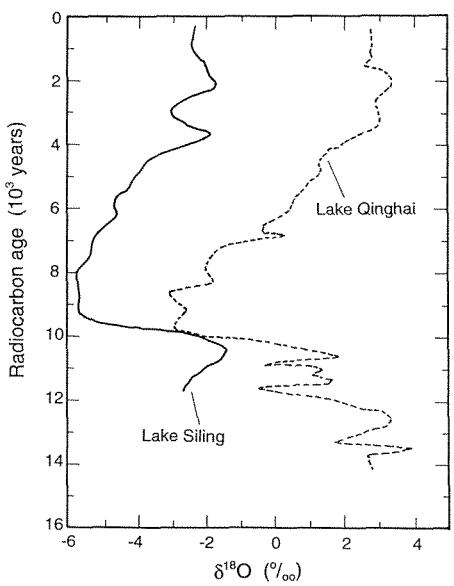

Fig. 5 Changes of the $\delta^{18}O$ of calcite deposited during the Holocene in two lakes located on the Tibet Plateau: Lake Siling, located in the central part of the plateau, about 300 km northwest of Lhasa (Morinaga *et al.*, 1993); and Lake Quinghai, located about 1300 km northeast of Lake Siling (Lister *et al.*, 1991) in the northeast corner of the plateau. Pronounced minimum of $\delta^{18}O$ around 9000 radiocarbon years BP reflect a maximum intensity of the Indian monsoon.

the Indian monsoon throughout the whole Holocene. Figure 5 shows that from *ca.* 10 thousand years BP to 6 thousand years BP, the Indian monsoon must have been much stronger than it is today, reaching the latitude of Quinghai lake (*ca.* 37°N). The $\delta^{18}O$ profiles indicate that the most intense phase of the monsoon lasted from *ca.* 9.5 and 8 thousand years BP, with its gradual weakening until about 3 thousand years BP, when it reached the present day strength.

Groundwater

Climatic influences on groundwater composition (stable isotope content, noble gas content and conservative chemical species) are preserved in aquifers which contain groundwater continuously or intermittently recharged between the late Pheistocene and the Holocene. These climatic signals are dependent upon the regional climate changes for the aquifer location. The preservation of the isotope signal within the groundwater system is influenced by both the geological setting and hydrodynamic dispersion (Stute & Schlosser, 1993).

The isotopic composition of groundwater generally reflects the weighted mean isotopic composition of the precipitation in the recharge area. This has been proved valid for a number of aquifers located in various climatic zones (Fig. 6). Consequently, the climate-induced variations of the stable isotope content of precipitation will be reflected by the isotopic composition of the groundwater. In fact, a change in the stable isotope composition of groundwater marking the transition from the Late Glacial to Holocene has been identified in many aquifers containing waters of different ages (e.g. Arnason, 1976; Rozanski, 1985; Phillips *et al.*, 1986; Heaton *et al.*, 1986; Kimmelmann *et al.*, 1989; Stute, 1989; Ferronsky *et al.*, 1991; Love *et al.*, 1994); Dutton, 1995). It is apparent from Fig. 6 that the depletion in the heavy isotope content of precipitation during the glacial period was a widespread phenomenon and not only confined to high latitudes.

Noble gas contents of groundwaters enable the temperature at the water table to be determined within ±0.5°C (Stute & Schlosser, 1993). This produces a conservative temperature record when the groundwater enters the confined zone and reflects an average ground temperature for a period of some decades. Studies of dissolved noble gases in regional aquifer systems of North and South America, Europe and Africa have revealed a temperature difference between the Holocene and the LGM of about 5°C (Stute *et al.*, 1995a,b). These results, along with the low latitude ice core results (Thompson *et al.*, 1995), challenge the widely adopted CLIMAP reconstructions (CLIMAP, 1981) for the low latitude regions (less than 2°C for the tropical ocean) and have important implications for the modelling of global climate.

Other archives

Apart from lakes, carbonates precipitated from surface waters or shallow groundwaters can be found in many continental locations in a great variety of forms

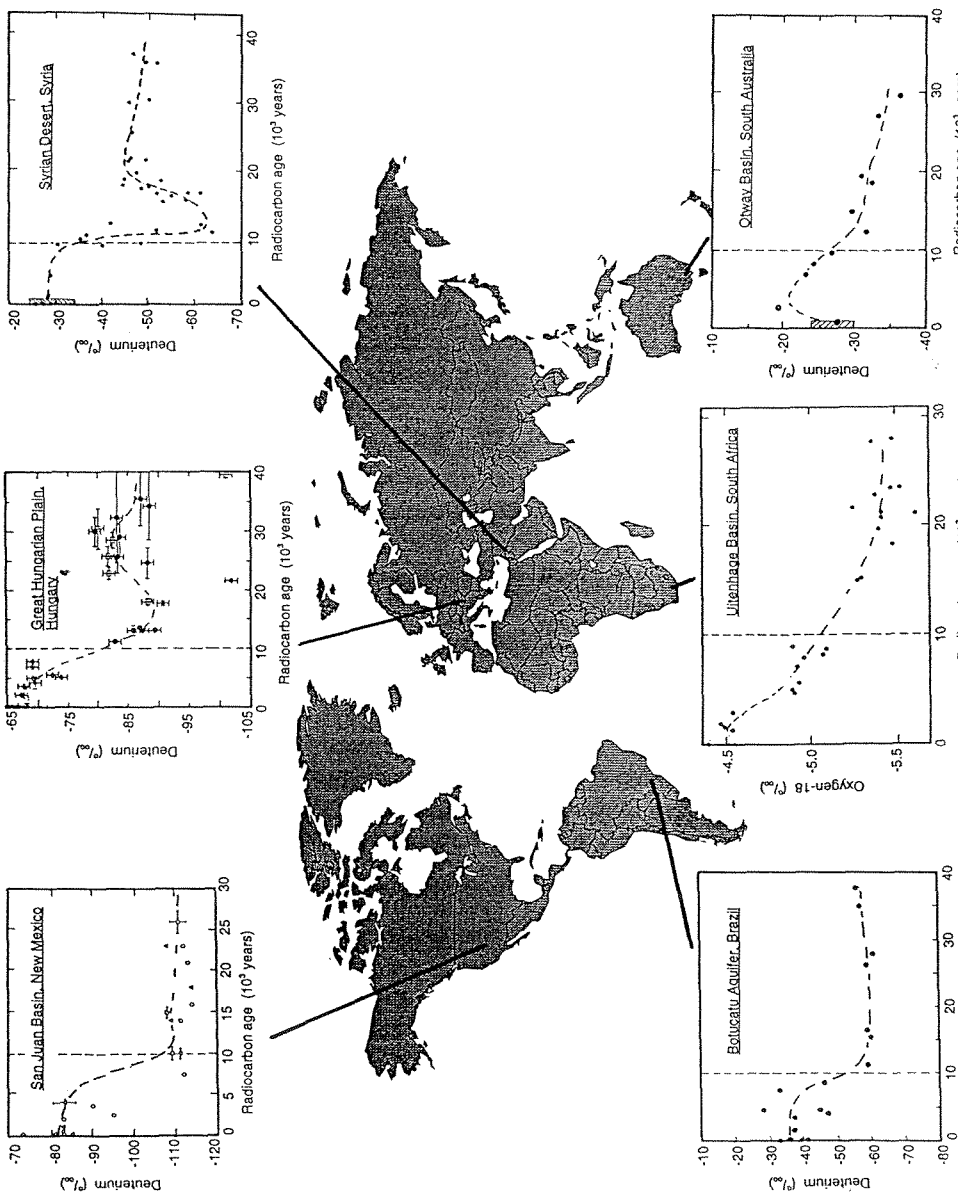

Fig. 6 Change of δ^2H and $\delta^{18}O$ of groundwater in selected aquifers of both hemispheres during the transition from late Glacial to Holocene (data from Phillips *et al.*, 1986; Heaton *et al.*, 1986; Kimmelmann *et al.*, 1989; Stute, 1989; Ferronsky *et al.*, 1991; Love *et al.*, 1994). The age of groundwater is inferred from its radiocarbon content.

(speleothems, calcretes, calcite veins, etc.). Among them, carbonate cave deposits called speleothems have proved to be an especially promising material for palaeoclimatic reconstruction. Speleothem usually precipitate slowly from percolating water over long periods of time, in conditions close to thermodynamic equilibrium, in an environment where seasonal variations of temperature, atmospheric humidity and isotopic composition of water and dissolved carbon are smoothed out. Consequently, only long-term climatic variations are expected to be recorded by the isotopic composition of calcium carbonate and of water inclusions trapped in speleothems or in calcite veins (e.g. Schwarz & Yonge, 1983; Winograd *et al.*, 1992).

There have been extensive efforts to derive climatologically relevant information from the isotopic composition of terrestrial organic matter (Edwards, 1993). A great variety of materials has been tested in this respect (peat, wood, bone, grains, etc.). The oxygen, hydrogen, carbon and nitrogen isotopic composition of organic matter is formed through a complex chain of processes and chemical reactions with both equilibrium and kinetic fractionation steps involved. Although the linkage between isotope signatures preserved in fossil organic matter and climate-related environmental factors is generally complex, it is often possible to derive quantitative climatic information from these materials.

INTERPRETATION OF ISOTOPE RECORDS

To assess the potential of stable isotope composition of meteoric water as a proxy indicator of climate, one should investigate its relationship to three major descriptors of climate: (a) surface air temperature; (b) amount of rainfall; and (c) transport of water vapour in the lower atmosphere. The available data on the isotopic composition of precipitation gathered over the last three decades, mainly through the IAEA/WMO Global Network "Isotopes in Precipitation", suggest that, at a first approximation, the temperature controls the isotopic composition of precipitation over high and mid-latitudes, whereas the amount of precipitation is a dominating factor in tropical regions. Atmospheric circulation patterns, linking the vapour source regions with precipitation sites, are of importance in both cases.

Table 1 summarizes the seasonal and long-term sensitivity of $\delta^{18}O$ of precipitation with respect to changes of temperature and amount of rainfall, derived from the IAEA/WMO database. The long-term $\delta^{18}O$–temperature coefficient varies

Table 1 The seasonal and long-term sensitivity of the ^{18}O isotope composition of precipitation to changes of ground level air temperature (in ‰ per °C) and the amount of rainfall (in ‰ per 100 mm), derived from the IAEA/WMO database.

	Temperature:		Amount of precipitation:	
	Seasonal	Long-term	Seasonal	Long-term
Mid- and high latitudes	~0.3	~0.5–0.9	lack of correlation	lack of correlation
Tropics	apparent negative correlation	?	~–1.3 to –1.9	~–0.6 to –1.7

for mid- and high latitudes in a relatively wide range, from 0.5 to 0.9‰ per °C. In the tropics, an apparent negative correlation between $\delta^{18}O$ and amount of precipitation is observed, both on a seasonal and interannual basis.

The quantitative interpretation of isotope records preserved in various continental archives in terms of climatic changes requires that: (i) the sensitivity of the isotopic composition of precipitation to the long-term fluctuations of key climatic parameters (temperature, precipitations amount, relative humidity) for the given area is known; and (ii) the isotope transfer function relating the climate-induced changes of the isotopic composition of precipitation with the isotope variations preserved in the given archive is well established. The isotope transfer functions should be constructed for each type of archive and for each site/region separately. Depending on the time scale involved, they may also be time dependent.

Because the isotopic composition of precipitation has been monitored only for the past three decades and, consequently, the long-term climatic sensitivity of the isotopic signature of precipitation is known with a relatively high uncertainty (*cf.* Table 1), independent ways of estimating this parameter are needed. This can be done for archives where both the isotopic composition of precipitation and temperature are independently recorded.

On the Greenland ice sheet, the present mean annual $\delta^{18}O$ of the snow is closely related to the mean annual surface temperature, T, expressed in °C, by the formula (Johnsen *et al.*, 1989):

$$\delta^{18}O = 0.67T - 13.7‰ \quad (1)$$

The temporal relationship between $\delta^{18}O$ and the temperature on the ice sheet can be inferred by reconstructing the measured borehole temperature profile and assuming a surface temperature history, as determined by a simple relationship to the well dated $\delta^{18}O$ profile. The parameters defining the relationship are determined by a least square fit of the modelled temperature profile to the measured temperature profile. Calibration for short term temperature changes can only be done for the past several hundred years, based on the data obtained from shallow cores (Johnsen, 1977; Cuffey *et al.*, 1994). Deep ice core and borehole temperature data provide information for performing such calibration for very long-term temperature changes (Dahl-Jensen & Johnsen, 1986; Cuffey *et al.*, 1995; Johnsen *et al.*, 1995a). In the modelling of the GRIP temperature profile, a second order dependency on $\delta^{18}O$ was allowed and corrections were made for the past $\delta^{18}O$ variations of sea water. Figure 7 shows the relationship between surface temperature and $\delta^{18}O$ of snow, derived from equation (1) and from the long-term borehole temperature calibrations obtained from GISP 2 (Cuffey *et al.*, 1995) and GRIP (Johnsen *et al.*, 1995a) deep holes. For the low $\delta^{18}O$ values (–42‰) found during the last glacial maximum at 20 thousand years BP (Fig. 1), both calibrations show some 20°C colder temperatures in Greenland than at present. Consequently, for the deglaciation period (*ca.* 20–10 thousand years BP) the apparent $\delta^{18}O$–temperature coefficient amounts to about 0.33‰ per °C.

In Antarctica, the 6‰ lower $\delta^{18}O$ during the last glacial period found for the Vostok core, as compared to the present day values, has been interpreted as a 5–6°C

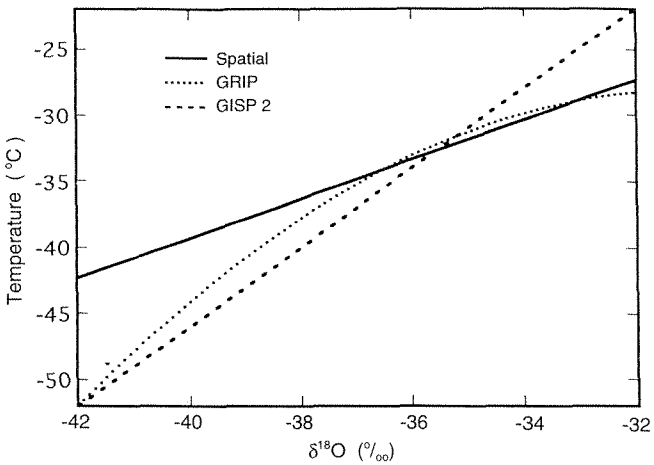

Fig. 7 The relationship between surface temperatures and the $\delta^{18}O$ of ice in Greenland. The spatial relationship (equation (1)) is shown as the heavy line. For long-term temporal changes: the dotted curve shows the GRIP temperature profile calibration (Johnsen *et al.*, 1995) and the dashed line the GISP 2 temperature profile calibration (Cuffey *et al.*, 1995).

colder temperature in Vostok for the last glacial maximum (Lorius *et al.*, 1985; Jouzel *et al.*, 1987a). The calibration of borehole temperature data for the Vostok core (Salamatin *et al.*, 1994) suggests only a few degrees larger temperature difference between the last glacial maximum and the Holocene in Antarctica than that derived from isotope data, which is a change significantly smaller than the 20°C found in central Greenland. This apparent asymmetry in cooling of the polar regions of both hemispheres during the last glacial period needs to be further investigated.

As discussed above, the ^{18}O and ^{2}H contents of groundwater respond to long-term changes of the isotopic composition of precipitation, whereas dissolved noble gases reflect the temperature at the recharge zone. Consequently, continuously recharged large regional aquifers located at mid-latitudes can be used to address the question of long-term sensitivity of isotopic composition of precipitation to changes of ground level temperature, on time scales corresponding to major climatic shifts such as the last deglaciation. The Great Hungarian Plain aquifer located in central Europe was extensively investigated for both its stable isotope composition and its noble gas content of groundwater (Stute, 1989). The apparent increase of $\delta^{18}O$ in groundwaters of the region during the transition from the late Glacial to the Holocene amounts to about 2.5‰ and was accompanied by a change of surface air temperature by around 7°C, derived from the noble gas content in these waters. Thus, the resulting apparent $\delta^{18}O$–temperature coefficient is about 0.36‰ per °C. This value, if corrected for the change of $\delta^{18}O$ of the ocean during the late Glacial–Holocene transition (approximately 1.3‰—Shackleton, 1987) is close to the long-term $\delta^{18}O$–temperature coefficient derived from the instrumental record of $\delta^{18}O$ in precipitation and surface air temperature in Europe, available for the last three decades (Rozanski *et al.*, 1992). It is worth noting that the apparent $\delta^{18}O$–temperature coefficient of

0.36‰ per °C for the last deglaciation period, obtained from groundwaters in central Europe, appears to be close to 0.33‰ per °C derived for the same period from borehole temperature calibrations of the two Summit ice cores (Cuffey *et al.*, 1995; Johnsen *et al.*, 1995a), although the absolute values and amplitudes of the $\delta^{18}O$ and temperature changes were very different for both regions.

CONCLUDING REMARKS

Stable isotope records of palaeo-precipitation preserved in various natural archives are among the most promising proxies of past climate changes. Under favourable circumstances, they are capable of providing high resolution (annual to decadal) records of past climates for the last climatic cycle. However, rules for quantitative interpretation of these records need to be further developed. In particular, the sensitivity of the stable isotope composition of precipitation with respect to long-term fluctuations of key climatic parameters (temperature, precipitation, relative humidity) in different climatic zones as well as its possible temporal variability on various time scales has to be quantified. In addition, the isotope transfer functions relating the climate-induced changes of the isotopic composition of precipitation with the isotope signatures preserved in various natural archives should be established. Moreover, their sensitivity to changes in the hydrological cycle (relative importance of evaporative flux, modifications of recharge mechanisms through changes in the seasonal distribution of precipitation and/or plant cover, etc.) need to be assessed.

Polar ice cores have proved to be a very rich source of information about changes of climate during the last glacial cycle. The high sensitivity of polar regions to climatic forcings, particularly in the northern hemisphere, have allowed the reconstruction of the late Pleistocene climatic fluctuations at high latitudes with unprecedented precision. It remains to be shown to what extent the climatic changes recorded in ice cores are mirrored at mid and low latitudes. High alpine glaciers and other natural archives located at these regions (lacustrine deposits, corals, groundwater, fossil organic matter, etc.) should provide more information about the climatic linkage of high and low latitudes of both hemispheres. Moreover, high resolution reconstructions of hydroclimatic changes during the late Glacial and Holocene are essential for the further development of realistic models of evolution of climate at mid- and low latitudes, where the majority of human population is living.

Recent attempts to model the behaviour of stable isotopes in the water cycle using Global Circulation Models showed that the isotopic composition of precipitation should be viewed not only as a climatic proxy but also as an additional hydrometeorological parameter and diagnostic tool for the modelling of changes in the water cycle, both on a regional and global scale.

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