Were the tropics significantly cooler during the last glacial maximum?

Des tropiques plus frais qu'aujourd'hui au dernier maximum glaciaire ?

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ABSTRACT – A paleotemperature record derived from noble gases dissolved in groundwater indicates that lowland equatorial Brazil has been about 5 °C cooler during the glacial maximum than today. This new evidence contradicts the long-held belief that the tropical regions maintained their warm climate during the last glacial maximum. It appears now that the tropical Americas are characterized by a temperature sensitivity comparable to that in higher latitudes.

Keywords: paleoclimatology, groundwater, hydrology, ice age, noble gases, radiocarbon, paleohydrology.

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RÉSUMÉ – Un enregistrement des paléotempératures dérivé des gaz nobles dissous dans les eaux souterraines indique que les régions de basse altitude du Brésil équatorial étaient environ 5 °C plus fraîches qu'aujourd'hui pendant le dernier maximum glaciaire. Ainsi, l'Amérique tropicale paraît avoir une sensibilité vis-à-vis des changements de température comparable à celle des hautes latitudes.

Mots clés : paléoclimatologie, eaux souterraines, hydrologie, âge glaciaire, gaz rares, radiocarbone, paléohydrologie.

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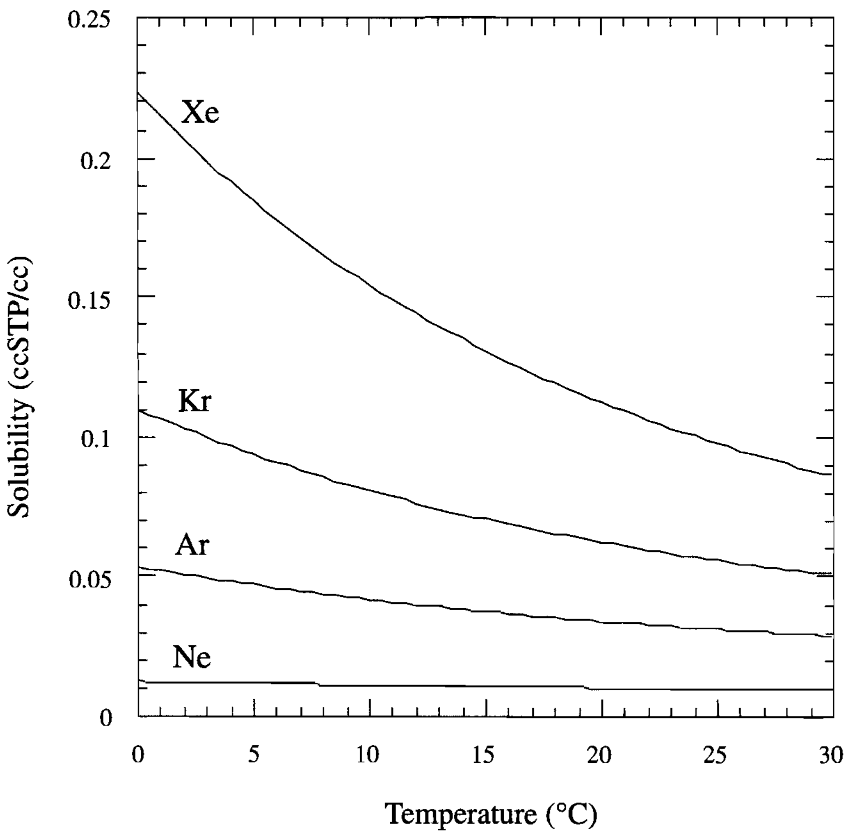

FIGURE 1.

Temperature dependence of the noble gas solubilities in fresh water expressed as Bunsen-coefficients (volume of dissolved gas under standard pressure and temperature per volume of water when equilibrated with the gas at standard pressure).

Relations entre température et solubilité des gaz nobles en eau douce, exprimées par les coefficients de Bunsen (volume des gas dissous par volume d'eau, sous conditions standard de pression et de température lorsque l'équilibre avec le gaz à pression standard est atteint).

INTRODUCTION

The current notion that glacial temperatures in the tropics were about the same as today rests primarily on paleoceanographic evidence. In the 1970's, a global map of glacial sea surface temperatures was reconstructed, based on faunal abundances in ocean sediment cores (CLIMAP, 1981). The CLIMAP paleotemperature records indicate that tropical sea surface temperatures during the LGM (last glacial maximum) were, at most, 2 °C lower than today. In the mid 1980's, this finding was confirmed by oxygen isotope records obtained from foraminiferas in ocean sediments (Broecker, 1986).

On the other hand, evidence from the tropical Americas shows that the altitude of snow lines and characteristic vegetation zones was about 1 000 m lower during the LGM as compared to today (e.g. Rind and Peteet, 1985; Clapperton, 1993). Recent work on ice cores from tropical Peru reaching back into the last glacial maximum found a strong oxygen isotope ratio signal in glacial ice (Thompson *et al.*, 1995). These data indicate a significant cooling of the tropics at high altitudes (between 2 500 m and 6 000 m), most likely of the order of 5 °C, or even more. Low elevation records of vegetation changes also point to lower glacial temperatures. However, their quantitative interpretation appears to be more difficult than at higher elevation. An increased vertical temperature gradient (lapse rate) during the LGM could possibly reconcile the different degree of cooling of tropical ocean surfaces and high elevation continents. However, it is not clear how the tropical lapse rate could have been changed that much during the last glacial maximum (Rind and Peteet, 1985).

The application of new techniques to reconstruct sea surface temperatures has yielded conflicting results. Sr/Ca and oxygen isotope ratios obtained from corals at Barbados, indicate a temperature change consistent with the continental records (5 °C, Guilderson *et al.*, 1994). However, another technique, using the ratio of large organic molecules (Alkenones) in sediments of the equatorial Atlantic as a paleothermometer, seems to confirm the glacial sea surface temperature reconstructions based on faunal abundances and oxygen isotopes (e.g. Sikes and Keigwin, 1994).

A new continental paleotemperature record has been derived recently from atmospheric noble gases dissolved in glacial groundwaters (Stute *et al.*, 1995b). The study site is located in northeastern Brazil at low elevation (400 m) close to the coast (500 km distance), and therefore fills the gap between high altitude continental and oceanic records.

NOBLE GAS THERMOMETER

The principle of the "noble gas thermometer", first proposed in the early seventies (Mazor, 1972) is based on the temperature dependency of the solubility of noble gases (neon, argon, krypton, and xenon) in water (Fig. 1, from Stute and Schlosser, 1993). While water percolates through the unsaturated soil zone, gases are continuously exchanged with air. The last equilibration takes place at the water table where the water enters the saturated zone, typically a few meters to several tens of meters below the surface. As a result, noble gas concentrations in groundwater reflect the temperature at the water table. In most cases, the measured noble gas concentrations exceed the ones expected due to solubility equilibrium at the water table. This additional component, termed "excess air" (Heaton and Vogel, 1981), is most likely caused by fluctuations of the water table trapping small air bubbles that are then partially or totally dissolved under increased hydrostatic pressure. Some of this excess air may subsequently be lost by a secondary gas exchange across the water table. The three unknowns, (i) temperature at the water table, (ii) amount of excess air, and (iii) degree of loss of excess air by secondary gas exchange, are obtained in an iterative procedure by optimizing the agreement of the four noble gas temperatures.

It has been demonstrated that in suitable ground water flow systems (aquifers) the measured noble gas concentrations, after subtraction of excess air, closely reflect the mean annual soil temperature at the water table in the recharge area (Stute and Schlosser, 1993).

GROUNDWATER AS AN ARCHIVE OF CLIMATE

Confined aquifers, for example, sandstone layers embedded in clays, appear to be the best paleoclimate archives. Typical flow velocities in confined aquifers are of the order of 1 m/y. Theoretically, a 30 km long aquifer should yield a 30,000 year paleoclimate record. The only reliable tool for dating glacial groundwater, the radiocarbon technique, limits the accessible time scale to about 30,000 years. Groundwater radiocarbon ages are characterized by a typical uncertainty of a few thousand years because carbon dissolved in groundwater is affected by chemical reactions in the aquifer. In addition, small-scale mixing processes smooth the recorded climate signal. However, model calculations and several pilot studies have shown that the last glacial to interglacial climate transition is often well preserved in an aquifer. A multitude of methods has been applied to derive paleoclimate information from this archive (Fontes *et al.*, 1993).

The disadvantages of the noble gas thermometer compared to others used to reconstruct continental climate records, such as, for example, vegetation changes as recorded in lake sediments, are its limited time resolution and dating uncertainty. The advantages are that it is based on a relatively simple physical principle and that the derived temperature reflects (multi-) annual mean temperatures with a high precision (0.5 to 0.8 °C). Noble gas paleotemperature records have been reconstructed for several sites in Europe, North America, South America and Africa (for a review see: Stute and Schlosser, 1993).

NOBLE GAS PALEOTEMPERATURES FOR BRAZIL

The first noble gas temperature record in the tropics has been derived recently from a confined aquifer in the Maranhão Basin at 41.5 °W (latitude) and 7 °S (longitude) in the central part of the semi-arid Piaui province in northeastern Brazil (Stute *et al.*, 1995b). Excess air in the water samples was found to be fractionated relative to atmospheric air and an optimization procedure was applied. Samples were dated with the radiocarbon technique after correcting for hydrochemical alterations in the aquifer by using a model by Fontes and Garnier (1979). The noble gas temperatures as a function of radiocarbon age cluster in two groups (Fig. 2). The average noble gas temperature of the water samples characterized by radiocarbon ages of less than about 10,000 years and therefore recharged at temperatures very similar to today's, 29.6 ± 0.3 °C agrees well with the mean annual soil temperature in the area, 29.1 ± 1.2 °C (± 0.3 °C is the standard deviation of the mean value, $\sigma/\sqrt{n}$). There is evidence based on its helium concentration that the sample in the upper right corner of the plot is much older than the remaining samples suggesting a formation during a warmer period. The difference between the average noble gas temperatures for the present interglacial (radiocarbon age $< \approx$ 10,000 years) and the last glacial maximum (radiocarbon age $> \approx$ 10,000 years) is 5.4 ± 0.6 °C (for a more detailed discussion of this record, see Stute *et al.*, 1995b).

IMPLICATIONS FOR CLIMATIC CHANGE IN THE TROPICS

The estimate of an ≈ 5 °C cooler climate at the LGM is consistent with the lowering of the snow lines and vegetation zones, and with the oxygen isotope ratios of the ice cores at high elevation in the tropical Americas. It appears that a change in the lapse rate cannot be used anymore to reconcile the different degree of cooling on the continents and the oceans. A cooling by at least 5 °C has also been found at numerous sites in the Americas in a wide belt between a latitude of 40° north and south of the equator. Two of these records (Texas, 29 °N, and New Mexico, 38 °N) were derived from noble gases in groundwater (Stute *et al.*, 1995a). Cooler glacial continental tropics are also consistent with the Sr/Ca and oxygen isotope record derived from corals in Barbados (Guilderson *et al.*, 1994). The combined evidence suggests that during the LGM, the latitudinal temperature gradient had not been increased

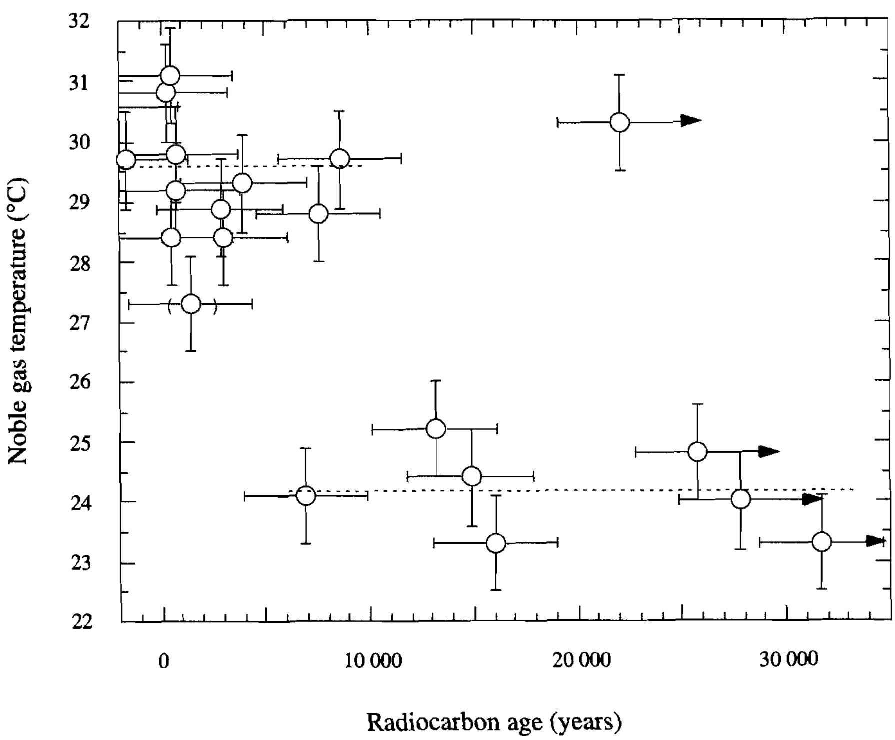

FIGURE 2.

Noble gas paleotemperature record derived from an aquifer in the Piaui province, northeastern Brazil. The arrows identify the samples with a radiocarbon content below the detection limit. Their ages may be higher than indicated.

Paléotempératures estimées à partir des gaz nobles dans un aquifère de la Province de Piaui, Nord-Est du Brésil. Les flèches indiquent les échantillons dont la teneur en radiocarbone est inférieure à la limite de détection. Leur âge peut être supérieur à l'âge indiqué.

as previously believed, but that the tropical and subtropical Americas were uniformly cooler.

If the hypothesis of cooler tropics can be extended to the tropical oceans, our current understanding of how the climate system worked during the glacial period will have to be revised. Current ideas of latitudinal heat transport by the ocean or the atmosphere, for example, would have to be revised. Also, atmospheric general circulation models (GCMs) that are being applied to predict future climate change, have been used to describe the climate during the LGM. Most of these model runs used CLIMAP's sea surface temperatures as a boundary condition and consequently would have to be redone.

However, the serious disagreement between continental and coral records, on one hand, and sea surface temperature records based on faunal abundances, oxygen isotope ratios, and alkenones, on the other hand, remains unresolved and needs to be studied further.

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