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A relief-specific model of the ice age on the basis of uplift-controlled glacier areas in Tibet and the corresponding albedo increase as well as their positive climatological feedback by means of the global radiation geometry

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ABSTRACT: The onset of the ice age era at ~2.75 Ma BP and its increasing intensity from ~1 Ma BP onwards cannot be explained by variations of the Earth's orbit. Evidence supporting a 2.4 million km^2 ice sheet on the Tibetan plateau during the Last Glacial Maximum has led to the hypothesis that the resulting albedo-induced heat loss in the Earth's atmosphere may have triggered global ice ages. Recent data obtained from marine and terrestrial sediment records now confirm the climatic-ecological impact of a Tibetan glaciation; they also show that the development of Tibet's ice sheet was synchronous with the onset and intensification of global ice ages.

KEY WORDS: Ice ages · Tibetan ice sheet · Quaternary climate

1. INTRODUCTION

The $\delta^{18}O$ records of planktonic foraminifera (Shackleton et al. 1988, Morley & Dworetzky 1991, Tiedemann et al. 1994) have shown that the Quaternary ice age began at about 2.75 Ma BP; from ~1 Ma BP onwards, its intensity (ice volume) and the length of its glacial phases approximately doubled (Fig. 1b). It is now recognized that the explanation of these events cannot be found in variations of the Earth's orbital parameters (Berger et al. 1999). Insolation variations (Fig. 1a) — which have displayed the same patterns for tens of millions of years (Berger & Loutre 1991) — account for the waxing and waning of global ice volumes to a limited degree (Hays et al. 1976), but to explain why ice ages occur at all and why they increased so rapidly during the past 1 Ma, we must look for a completely different, terrestrial cause.

In recent years, the continuous decline in levels of the greenhouse gas CO_2 in the atmosphere and a concomitant global cooling have been considered to be the most likely cause (Broecker 1995, Ruddiman et al. 1997). Computer simulations by Berger et al. (1999) show that, to trigger ice ages in this way, atmospheric CO_2 must have decreased from more than 320 parts per million by volume (ppmv) to 200 ppmv during the past 3 Ma. However, the latest alkenone-based CO_2 estimates (Pagani et al. 1999, Pearson & Palmer 1999) have shown that, in spite of high temperatures, CO_2 levels during the Tertiary were by no means higher — sometimes even lower — than the preindustrial value of 270 ppmv in postglacial times or >300 ppmv during the Eem Interglacial (Fischer et al. 1999). So there is still no evidence for a decrease in atmospheric CO_2 concentration since the Tertiary/Quaternary transition that may have caused temperatures to fall. Furthermore, the fine-scale records of the GRIP ice core confirm that during the last 3 glaciations the CO_2 values lagged climatic change by as much as several thousands of years (Fischer et al. 1999, Mudelsee 2001). This reverses the previously accepted causal nexus: evidently, atmospheric CO_2 concentrations changed in

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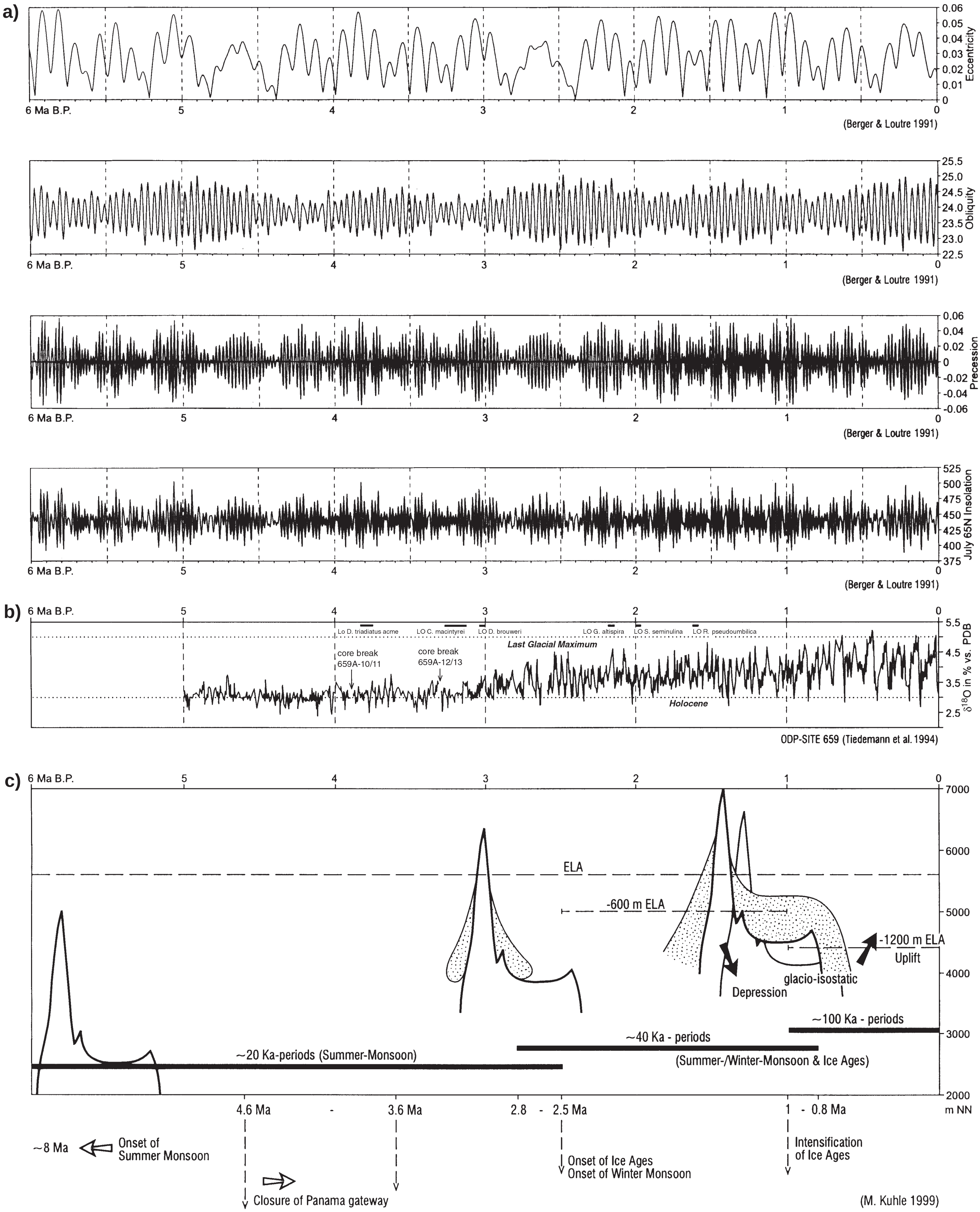

a)
Eccentricity
6 Ma B.P.
(Berger & Loutre 1991)
Obliquity
Precession
July 65N Insolation
b)
Lo D. triadiatus acme
LO C. macintyrei
LO D. brouweri
LO G. altispira
LO S. seminulina
LO R. pseudoumbilica
Last Glacial Maximum
core break 659A-10/11
core break 659A-12/13
Holocene
$\delta^{18}O$ in ‰ vs. PDB
ODP-SITE 659 (Tiedemann et al. 1994)
c)
ELA
-600 m ELA
-1200 m ELA
Uplift
glacio-isostatic
Depression
~100 Ka - periods
~40 Ka - periods
(Summer-/Winter-Monsoon & Ice Ages)
~20 Ka-periods (Summer-Monsoon)
4.6 Ma - 3.6 Ma
2.8 - 2.5 Ma
1 - 0.8 Ma
m NN
~8 Ma
Onset of Summer Monsoon
Closure of Panama gateway
Onset of Ice Ages
Onset of Winter Monsoon
Intensification of Ice Ages
(M. Kuhle 1999)

the wake of glacial-interglacial transitions, rather than promoting them.

The hypothesis that the closure of the Panamanian seaway and the resulting North Atlantic deep water formation were responsible for the onset of the ice ages (Haug & Tiedemann 1998) is still inconclusive. Closure occurred 4.6 to 3.6 Ma ago, i.e. 1 Ma too soon. The argument that increasing obliquity amplitudes between 3.1 and 2.5 Ma BP caused the ice to build up contradicts the fact that the decrease in obliquity amplitudes between 1 and 0.8 Ma does not coincide with ice retreat; on the contrary, it corresponds in time with an intensification of global glaciation (Fig. 1a,b).

Long-term global climatic changes may also have been caused by Cenozoic plateau uplift (especially of the Himalaya-Tibetan and the North American plateaux), inducing a change of zonal wind and precipitation patterns and a steepening of the climatic south-north gradient (Ruddiman & Kutzbach 1992). However, uplift of the Tibetan plateau started 20 Ma BP ago (Harrison et al. 1992, Copeland 1997) and, as the onset of the summer monsoon suggests, it began to act as a climate-effective barrier some 8 Ma ago (Prell & Kutzbach 1992, Tiedemann et al. 1994, De Menocal 1995) — too early for the start of the ice ages.

2. TIBETAN ICE SHEET AS AN ICE AGE TRIGGER

It has been shown that the Tibetan plateau produces effects on wind patterns similar to those observed at the present time when average elevations of 2000 to 2500 m are attained (Manabe & Broccoli 1985, Prell & Kutzbach 1992). Today, however, the 2.6 million km^2 plateau averages 4600 m. In the course of this uplift from 2000 to 4600 m, the plateau surface must have reached and crossed significant climatic thresholds. Such an event at the Tertiary-Quaternary transition must have had a dramatic impact on the global climate. At elevations of 4000 to 4300 m a seasonal winter snow cover and small glaciers would have formed; from ~4600 m onwards (its present height), the plateau would have entered a climatic zone where even slight temperature declines (2 to 3°C) could lead to an extensive ice sheet.

The presence of such a 2.4 million km^2 ice sheet on the Tibetan plateau during the Last Glacial Maximum (LGM) has since been demonstrated by our studies of glacial landforms (Kuhle 1982, 1987, 1988, 1990, 1991, 1994, 1995, 1997, 1998, 1999) on the plateau and in the neighbouring mountain ranges of Kunlun, Qilian Shan, Karakorum and the Himalaya. In addition, dates of lake sediments on the central plateau have now confirmed the existence and time scale of this glaciation. The lakes in the area of the former ice sheet are all younger than 13 000 yr old because they developed only after the glaciers had melted (Kashiwaya et al. 1991, Van Campo & Gasse 1993, Avouac et al. 1996, Gasse et al. 1996). By contrast, lakes in nearby, nonglaciated areas such as the Qaidam basin and the Gobi Desert display continuous sediment records going back more than 40 000 yr (Chen & Bowler 1986, Pachur & Wünnemann 1995, Rhodes et al. 1996, Wünnemann & Pachur 1998).

At subtropical latitudes and high altitudes, insolation levels on the Tibetan plateau are close to the solar constant (Kuhle & Jacobsen 1988) and are therefore 4 times higher than in the areas formerly occupied by the Nordic ice sheets (Fig. 2). An ice-free plateau surface absorbs 80% of the incoming solar radiation and converts it into longwave radiation; it thus contributes substantially to the warming of the Earth's atmosphere. Our measurements have shown that snow-covered glaciers directly reflect 75 to 95% of the insolation, which is therefore lost to the global heat balance (Kuhle & Jacobsen 1988). Calculations indicate that during the LGM as much as 32% of the albedo-induced energy loss of the Earth's atmosphere was due to the ice sheet of the Tibetan plateau (Biele-

Fig. 1. (a) Astronomical parameters of the earth's orbit and rotation and corresponding insolation values for 65° N for the last 6 million yr according to Berger & Loutre (1991).
(b) Benthic oxygen isotope records from Ocean Drilling Program Site 659 according to Tiedemann et al. (1994). The fluctuations in the $\delta^{18}O$ content of the foraminifera (vs PeeDee belemnite) reflect the fluctuations of the global ice volume, with high values corresponding to the glacials and low values to the interglacials. Neither the beginning nor the intensification of the Quaternary glaciation period is correlated with the insolation in (a).
(c) Synopsis of the uplift and glaciation of the Tibetan plateau in their relation to other geoecological events. A comparison between (a) and (b) shows that an additional factor apart from orbital variations is required to explain both the start of the ice ages about 2.8 Ma and their increasing intensity from 1 Ma onwards. The closure of the Panama gateway occurred too early to be the terrestrial cause. The uplift of the Tibetan plateau, as far as it can be reconstructed from the onset of the summer and winter monsoons, and, derived from this, the begin of an autochthonous glaciation of Tibet from ~2.5 Ma BP onwards, were synchronous with the onset of the global ice ages. Evidence that variations of the summer and winter monsoon intensity documented by marine dust flux records and loess-palaeosol sequences on the Chinese loess plateau occurred in phase not with the insolation variation but with glacial-interglacial cycles (40 ka and ~100 ka periods) is a strong pointer to the existence of a Tibetan glaciation. Gradual uplift of the Tibetan Plateau towards the ELA (equilibrium line) level enabled an ice sheet of 2.4 million km^2 to grow from ~1 Ma BP onwards; the resulting cooling effect permitted a maximum expansion of the Nordic lowland ice sheets (–1200 m ELA). The subsequent glacio-isostatic depression, deglaciation and following rebound of the plateau were responsible for the occurrence and duration of interglacial-glacial cycles (~100 ka periods)

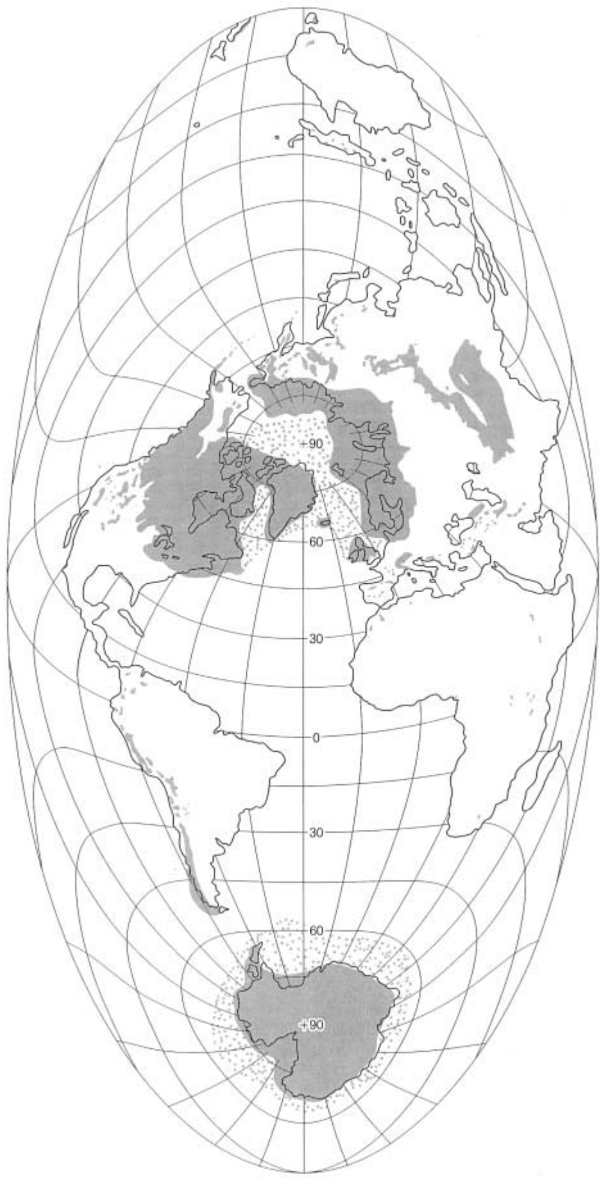

Fig. 2. Maximum extent of glaciated areas during the Last Glacial Maximum (LGM), based on an equal-area projection. Continental ice is indicated by a dense signature, marine ice by a sparse one. In comparison with the near-pole, lowland ice sheets, the 2.4 million km^2 Tibetan ice sheet is remarkable for its unique, extremely insolation-favoured, subtropical location with an average surface elevation of 6000 masl. The influence of a Tibetan glaciation is more than 4 times higher than that of a northern lowland glaciation of the same size, i.e. its albedo effect equals that of a ~10 million km^2 northern ice sheet. Based on Broecker & Denton (1990), modified after Kuhle (1982, 1987, 1988, 1990, 1991, 1994, 1995, 1997, 1998, 1999)

feld 1997). This effect must have been a strong promoter of ice build-up on a global scale.

But the consequences are even more far-reaching. Under present conditions, summer warming of the Tibetan plateau leads to areas of low surface pressure and hence to a marked atmospheric pressure gradient in relation to the relatively cold adjacent oceans. Strong winds are the result: the East Asian and the Indian summer monsoons (Findlater 1974). The pattern is reversed in winter, when the high albedo of the plateau's winter snow cover leads to cold-induced high surface pressure and thus to a compensatory flow of air to the low surface pressure areas over the now relatively warm oceans, i.e. the winter monsoon circulation (Flohn 1981, Ding et al. 1995, Xiao et al. 1995). Inevitably, the existence of a perennial Tibetan ice sheet must have modified this seasonally alternating large-scale pattern of monsoonal circulation. Whereas the summer monsoon would have been either weaker or non-existent (Sirocko et al. 1993), the winter monsoon must have been much stronger. Data are now available to document that these climatic-ecological effects did indeed occur. Deep-sea cores from the Arabian Sea allow the reconstruction of changes in the upwelling system off Arabia due to variations in strength of the SW Indian monsoon circulation. For the last 500 000 yr the data show that the summer monsoon was substantially weaker during the glacial phases, but the winter monsoon was stronger (Anderson & Prell 1993, Emeis et al. 1995). High-resolution loess-paleosol sequences from China spanning the last 2.5 Ma permit a reconstruction of the intensity fluctuations of the East Asian summer monsoon and supply further confirmation that the summer monsoon was dramatically weaker during glacial times (Rutter & Ding 1993). For the East Asian winter monsoon, however, the same sequences record a marked increase in intensity during glacial phases (Ding et al. 1995, Xiao et al. 1995). Both marine and terrestrial sediment records document a highly significant correlation between variations in global ice volumes and corresponding counterfluctuations of monsoon circulation throughout the entire ice age era.

3. CORRELATION BETWEEN TIBETAN UPLIFT AND THE ICE AGE

These results all confirm our glaciogeological findings: Tibet was indeed covered by an ice sheet during the LGM. In addition, the monsoon chronology reveals the start of the Tibetan plateau's impact on the climate (Fig. 1c). For the summer monsoon to occur, a plateau elevation of 2000 to 2500 m is required, which was attained around 8 Ma BP (Manabe & Broccoli 1985, Quade et al. 1989, Prell & Kutzbach 1992, Tiedemann et al. 1994). The winter monsoon additionally needs the albedo effect of seasonal snow cover (Flohn 1981, Ding et al. 1995, Xiao et al. 1995), requiring plateau elevations of 4000 to 4300 m. The remains of a widespread Hipparion fauna in Middle Pliocene sediments of central Tibet are indicators of a warm-tropical steppe climate and show that the altitude of the winter snow zone had not yet been reached at this time (Chen 1981, Ji et al. 1981). Only from 2.5 Ma BP onwards did sediment begin to accumulate on the loess plateau of China, thus recording the onset of winter monsoon circulation (Kukla & An 1989, An et al. 1990, Ding et al. 1992). As a result of the albedo of a winter snow cover at high subtropical insolation levels, the Tibetan plateau was, for the first time, an effective influence on the absolute heat balance of the Earth, at the same time as the Nordic ice sheets began to expand. Because its elevation was lower than it is today, the plateau had only a 25 to 50% ice cover at most, even during cold phases. Sensitivity experiments conducted by Marsiat (1994) have shown that under conditions of a reduced glaciation of Tibet the Nordic lowland glaciers also remained rudimentary. This correlates with marine $\delta^{18}O$ records according to which global ice volumes between 2.5 and 1 Ma BP were only half those during the late Pleistocene (Shackleton et al. 1988, Morley & Dworetsky 1991, Tiedemann et al. 1994). Glaciation of the Tibetan plateau could only reach its proven LGM extension of 2.4 million km^2 when today's average elevation of at least 4600 m had been attained, i.e. from ~1 Ma BP onwards, then inducing maximum global ice volumes. Interglacials occurred only when glacio-isostatic mechanisms caused the plateau areas to subside under the weight of a maximum ice thickness of 2.5 km (Kuhle 1995), thus enabling a complete deglaciation in phases of positive radiation anomalies.

Tibet's climatic impact first became effective when uplift raised the plateau to the level of the seasonal snowline from ~2.5 Ma BP onwards, and subsequently to the level of maximum glaciation starting at ~1 Ma BP. The progressive glaciation of the Tibetan plateau may thus have been the decisive terrestrial factor causing orbital variations to translate into global ice ages.

4. PROBLEMS AND POSSIBLE SOLUTIONS

Glacio-isostatic subsidence of the Tibetan plateau under ice pressure is a prerequisite for the occurrence of interglacial stages. The high uplift rates of 12 mm yr^{-1} measured in the region of the Tibetan plateau (Hsu et al. 1998) may be a first indication of glacio-isostatic recovery. The author's own observations of moraine deposits on the northern slope of Shisha Pangma, in the border area between the Himalayas and the Tibetan plateau, point in the same direction (Kuhle 1988). These extensive pedestal moraines were left by the ice during the late Last Glacial. Since then, small local plateau glaciers have formed on the moraine surfaces, which can only be explained by strong glacio-isostatic uplift in the meantime, thus raising the plateau closer to the local ELA (equilibrium line).

Kaufmann & Lambeck (1997, 2000 unpubl.) have shown that, on the basis of secular changes in geoid anomaly and free-air gravity anomaly, it is possible to distinguish the amount of glacio-isostatic uplift from uplift caused by tectonic movements. The predicted effects of the melting of an up to 2 km thick ice sheet on the Tibetan plateau are so profound that the current satellite missions CHAMP and GRACE would be able to identify them.

A further issue is the extent of the influence of the Tibetan ice sheet on the heat balance of the atmosphere and whether this was marked enough to have a decisive initial impact on the pattern of global ice ages. Only modeling results can provide an answer.

According to our theory the formation of the Nordic lowland glaciers depends on the cooling effect of a high-altitude Tibetan ice sheet, i.e. on a global scale the Tibetan plateau has to be most likely to develop an ice sheet and this has to form in advance of all other areas when temperatures start to fall. Using an atmospheric general circulation model (GCM), Verbitsky & Oglesby (1992) studied the evolution of ice sheets in relation to the atmospheric CO_2 concentration (i.e. temperature change) using a computed 'glaciation sensitivity' index. Their results showed that Tibet and Siberia were more likely to develop an ice sheet than Canada or Fenno-Scandinavia.

Similar conclusions were drawn by Marsiat (1994), who used a 3D climate model to simulate global ice growth generated by temperature changes caused by orbital variations. Here too, the first large ice sheet formed on the Tibetan plateau, followed by Siberia (in contrast to Verbitsky & Oglesby, Marsiat saw a strong glaciation tendency in Alaska too). Both models thus confirm our hypothesis that the Tibetan ice sheet played a foremost role in terms of time.

The latest modeling results presented by Kutzbach et al. (1998) are in agreeance with the above. However, these climate and biome simulations carried out using the Community Climate Model, Version 1 (CCM1), do not investigate the pattern of ice build-up but are based on the reconstructed glaciation conditions described in CLIMAP Project Members (1981), i.e. the Tibetan plateau is assumed to be non-glaciated. As model results show, there are still 'small areas of permanent snow-cover over non-glaciated areas of western Canada-Alaska, northern Eurasia between the Eastern Siberian and Western Eurasian ice sheets and over Tibet at 21 ka. This result indicates that the model would develop a larger area of glaciated land than actually appeared to have been present at 21 ka. The simulation of permanent snow cover over Tibet contributed to the reduction of the Asian monsoon at 21 ka.' (Kutzbach et al. 1998, p. 496).

That a Tibetan ice sheet not only influenced the monsoon but also had a global impact was demonstrated by a sensitivity experiment conducted by Marsiat (1994). By reducing the global albedo of snow-covered mountain areas, Marsiat attempted to prevent what he considered to be the unrealistic formation of ice sheets on the Tibetan plateau and the Rocky Mountains: 'although the mountainous areas were covered by ice after some period, the perturbation occurring at the beginning of the glacial cycle influences the remainder of the simulation, showing lower ice volumes during the entire glacial cycle.' This suggests that the albedo effect of the Tibetan ice sheet has a global impact.

In order to investigate this impact in greater depth, it is appropriate to use sensitivity experiments with circulation models that consider the Tibetan ice sheet to be a realistic possibility rather than a simulation error. It would make sense to place alternative simulations side by side, showing, on the one hand, the climatic effects of a glaciated Tibetan plateau—as reconstructed by the author on the basis of his empirical fieldwork—and, on the other, simulations based on the old view (von Wissmann 1959) of a non- or only slightly glaciated plateau, which is still being advocated by Derbyshire et al. (1991), among others. Sensitivity experiments with atmospheric circulation models could also be used to quantify the differential influence of the albedo of the various ice sheets on the global cooling balance.

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