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The palaeohydrology of the Late Pleistocene Lake Tauca on the Bolivian Altiplano and recent climatic fluctuations

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The palaeohydrology of the Late Pleistocene Lake Tauca on the Bolivian Altiplano and recent climatic fluctuations

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ABSTRACT. Applying the water budget to the palaeohydrology of the Late Pleistocene Lake Tauca (12 500 - 11 000 BP) on the Altiplano (South American Andes), several cases are discussed to show how the climatic conditions must have changed in comparison with the recent climate in order to make the formation of the palaeolake possible. It is shown that precipitation must have increased by at least 30 % in the entire Altiplano-basin in comparison with that of today. The example of the recent water budget fluctuations of Lake Titicaca shows that the conditions during the Tauca-period can best be explained by a southward shift of the atmospheric circulation belts in the area of the Altiplano.

INTRODUCTION

The Peruvian-Bolivian Altiplano is a closed topographic depression (Fig. 1). Since the northern part is higher and wetter, it is drained from north to south by the Desaguadero river which flows into a closed lake, the Lake Poopo. Today the southern Altiplano also includes the Salars of Coipasa and Uyuni.

The investigations by Servant and Fontes (1978) showed that three lacustrine transgressions have occurred since the Middle Pleistocene, which united the three basins to form a large lake. The Palaeolake Tauca, the last one, was formed in the Late Pleistocene between 12 500 and 11 000 BP. It covered 43 000 km^2 and had a maximal depth of 60 m. By about 10 000 BP Lake Tauca had been reduced to approximately the size of Lake Poopo. During the Holocene there were only small fluctuations of the lake levels. Kessler (1966) reported on recent variations and the formation of a new lake (Uru-Uru) on the southern Altiplano.

Mercer and Palacios (1977) were able to prove that the Last Glaciation in the Cordillera de Vilcanota and the Quelccaya ice cap in the area of the northern Altiplano culminated some time between about 28 000 and 14 000 BP. A rather minor readvance of the Quelccaya ice cap was in progress about 11 500 BP and culminated about 11 000 BP (Huancane II moraine). By 10 000 it was hardly, if at all, larger than it is today. The snow line depression during the Huancane II readvance was probably not more than 300 m.

Evidence of a Late Pleistocene glacier advance has also been found in other parts of the Altiplano catchment area (Cordillera de Apolobamba, Lauer 1982; Cordillera Real, Nogami 1970). The Huancane II readvance can also be compared with the oxygen isotope profile observed in the Dome C ice core of east Antarctica (Lorius et al. 1979). The ice core chronology indicates a relatively cold period from 11 000 to 13 000 BP.

The following is a reconstruction of the climate during the Huancane II readvance using the water budget equation for Lake Tauca. This method has already been tested on numerous closed lakes (e.g. Bobek 1937; Leopold 1951; Snyder and Langbein 1962; Kessler 1963; Grove and Pullan 1963; Haude 1969; Galloway 1970; Butzer et al. 1973; Kutzbach 1980).

Since Lake Tauca already existed during the Huancane II readvance, its presence during this period cannot be explained by an additional runoff from melting glaciers of the basin. Its origin must be due to changes in evaporation and/or precipitation. In any case it is remarkable that during the glacial retreat from position Huancane II to position Huancane I between 11 000 BP and 10 000 BP Lake Tauca dried out despite being additionally fed by melting glaciers during this period.

QUANTITATIVE ESTIMATES OF PAST EVAPORATION AND PRECIPITATION OF THE PALAEOLAKE TAUCA-PERIOD

In order to calculate the water budget of Palaeolake Tauca, the Altiplano was divided into several areas (Fig. 1 and Table 1). The figures for the recent situation are from Kessler (1963, 1970) and Kessler and Monheim (1968).

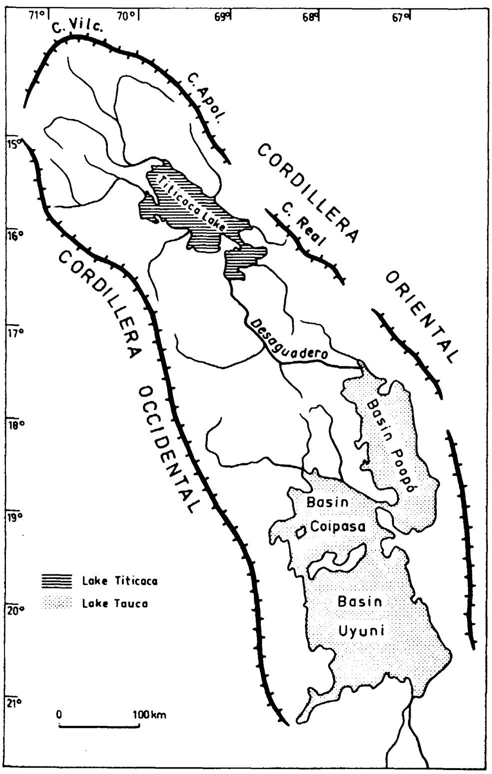

Figure 1. Late Pleistocene Lake Tauca and the Altiplano (Peru, Bolivia) according to Servant and Fontes (1978).

Table 1. Hydrological and climatological data of the Altiplano.

	Area (km^2)	Recent prec. (m/year)	Recent runoff coefficient
Area of northern Lake Tauca	22 700	0.31	
Area of southern Lake Tauca	20 300	0.18	
Catchment area of Lake Tauca without catchment area of Desaguadero river	73 500	0.22	0.07
Catchment area of Desaguadero river without catchment area of Lake Titicaca	30 250	0.45	0.07
Area of Lake Titicaca (Late Pleistocene)	9 700	0.93	
Catchment area of Lake Titicaca (Late Pleistocene)	48 400	0.73	0.21

The mean annual water budget of a closed lake at equilibrium can be expressed by the equation

$$P_L + R_C - E_L = 0$$

where P_L is the annual precipitation onto the lake, R_C is the mean total annual runoff from the catchment area and E_L is the mean annual lake evaporation. In the various case studies the increase in runoff from the catchment area which occurred together with a decrease in evapotranspiration due to temperature depression, was calculated with the water budget equation of the catchment area:

$$R_C = P_C - E_C$$

where P_C is the annual precipitation onto the catchment area, E_C is the annual evapotranspiration from the catchment area.

According to a diagram by Wundt (1953) the increase in runoff when the precipitation onto the catchment area increases implies an increase in relative humidity (RH) of the air in the basin (Table 2).

Table 2. The change in the runoff coefficient $K = R_c/P_c$ dependent on precipitation onto the basin P_c (according to Wundt 1953).

Pc(cm/year)	20	30	40	50	60	70	80	90	100	110	120	130
K	0.100	0.155	0.210	0.263	0.317	0.363	0.410	0.450	0.490	0.530	0.570	0.600

Evaporation from the lake and its change dependent on the surface temperature and relative humidity of the air was calculated with an aerodynamic bulk formula:

$$E_L = c\ f(u)(Q-q) = c\ f(u)(1-RH)Q$$

where c is a constant, f(u) is a function of the wind velocity, Q is the vapour pressure at the water surface and q is the vapour pressure of air. The decrease in evapotranspiration of the catchment area with decrease in temperature was calculated using the same factor as the evaporation from the lake surface.

For estimating the recent lake evaporation of the Altiplano the value for Lake Titicaca was used, namely E_L = 1.48 (m per year). But since the southern Altiplano is drier, E_L is probably somewhat higher. For this reason the following calculations represent the minimal conditions for an increase in precipitation. The maximal temperature depression for the Huancane II readvance (= 3 °C) was calculated from the snow line depression (300 m) and the temperature gradient of the air near the ground (0.8-0.9 °C/100 m, according to Kessler 1963).

RESULTS OF THE CALCULATIONS

The following individual cases will demonstrate the sensitivity of the model. Table 3 shows what percentage of the annual water supply would be represented by the precipitation onto Lake Tauca (A), the runoff from the catchment without discharge from Lake Titicaca (B), and the discharge from Lake Titicaca (C) in each case.

Case 1: $\Delta P = 0, \Delta E = 0, \Delta T = 0.$

What would have happened if the Palaeolake Tauca had been subject to today's climatic conditions, that is, if changes in precipitation, evaporation and temperature had not occurred? Our calculations show that the lake would have dried up in about 50 years. In this example the precipitation onto the Lake Tauca makes up 72% (Table 3).

Case 2: $\Delta P \neq 0, \Delta E = 0.$

The second question is: By how much must the precipitation in the entire basin be increased in comparison with today's conditions for the Palaeolake Tauca to exist? The annual precipitation amount would have to be increased by 85% all over the catchment area. As Table 3 shows, the discharge from Lake Titicaca would then supply 50% of the water for Lake Tauca.

Case 3: $\Delta E \neq 0, \Delta T \neq 0, \Delta P = 0.$

As already mentioned, a temperature decrease of 3 °C can be deduced from the snow line depression during the Huancane II readvance. This indicates a decrease in evaporation of 18% in comparison with the situation today. It can also be assumed that precipitation and relative humidity have not changed. This suggests that the existence of the Palaeolake Tauca was not secured. It would disappear in about 100 years. The water supply of the Palaeolake Tauca would be relatively equally distributed among all three components.

Case 4: $\Delta E \neq 0, \Delta T \neq 0, \Delta P \neq 0.$

This is based on the same conditions as in case 3. The deficit is compensated by an increase in precipitation. In the case of a decrease in evaporation by 18% due to the temperature, precipitation in the entire basin must be increased by 40% in order to guarantee the existence of the Palaeolake Tauca.

Case 5: $\Delta E \neq 0$, $\Delta T \neq 0$, $\Delta P \neq 0$, $\Delta RH \neq 0$ (Lake).

In calculating case 4 we take into account that the precipitation rise causes an increase in the relative humidity of the air close to the ground (RH) in the catchment area. In order to heighten the minimal conditions for a possible increase in precipitation it will also be assumed that the relative humidity over the sea surfaces increased by 5% compared with today's conditions. Taking the temperature change into consideration this would mean a decrease in E_L by a total of 27%. The necessary increase in precipitation (ΔP) would then still be as much as 30%.

Table 3. Mean annual water supply for the Palaeolake Tauca in percent.

A Precipitation onto Lake Tauca
B Runoff from the catchment without discharge from Lake Titicaca
C Discharge of Lake Titicaca

	A	B	C
Case 1	72	14	14
Case 2	32	18	50
Case 3	39	26	35
Case 4	29	25	46
Case 5	30	24	46

The results can be summarized as follows: The existence of the Palaeolake Tauca cannot be explained without assuming an increase in precipitation of at least 30% in the entire basin. Although the discharge from Lake Titicaca is of secondary importance for the water budget of the southern Altiplano today, it played a very important role during the Late Pleistocene for the Palaeolake Tauca (Table 3, case 5).

REFLECTIONS ABOUT THE PALAEOCLIMATE

It has been pointed out repeatedly (e.g. Heine 1977; Hays 1978; Flohn 1981; Mercer 1978; Salinger 1981; Street-Perrott and Roberts 1983) that during the period from 18 000 BP and 9400 BP (Southern Hemisphere thermal maximum) there was an unequal rise in temperature in the two hemispheres. This indicates that at least for a time there was a southward shift of the circulation belts.

The following climatic conditions exist on the Altiplano today (see Fig. 2). Tropical easterlies reach the basin during the rainy season from November to April. During the dry period from May to September/ October the area is influenced by the SE-Pacific anticyclone. Westerly winds prevail all over the troposphere. The axis of the subtropical jet stream shifts northwards to a latitude of about 20 $^{\circ}$ to 25 $^{\circ}$S. The position in summer time is at about 30 $^{\circ}$ to 35 $^{\circ}$S. During an occasional southward shift in comparison with today's position of the equatorial trough and the subtropical anticyclone belts, the summer rainy period in the Altiplano would have been lengthened during the Late Pleistocene. This assumption would best explain the Late Pleistocene climatic conditions.

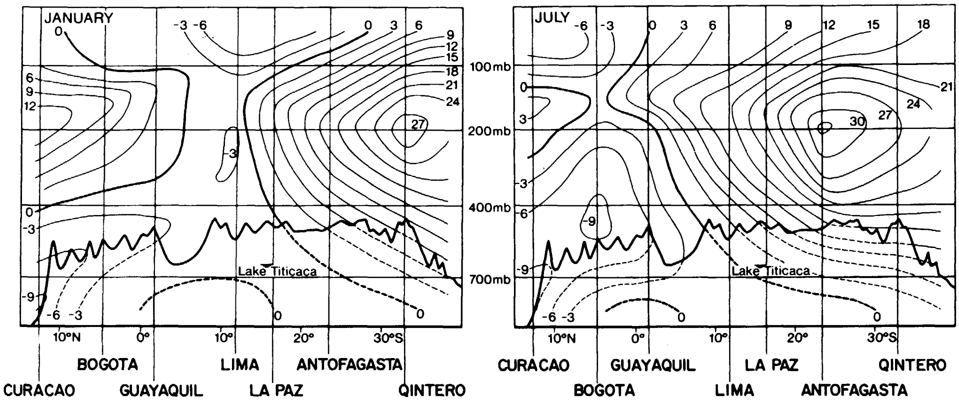

Figure 2. Mean cross-section of the zonal wind above the west of South America, with the peak line of the Andes. Zonal component of the resultant wind in m/s, positive values denote eastward flow.

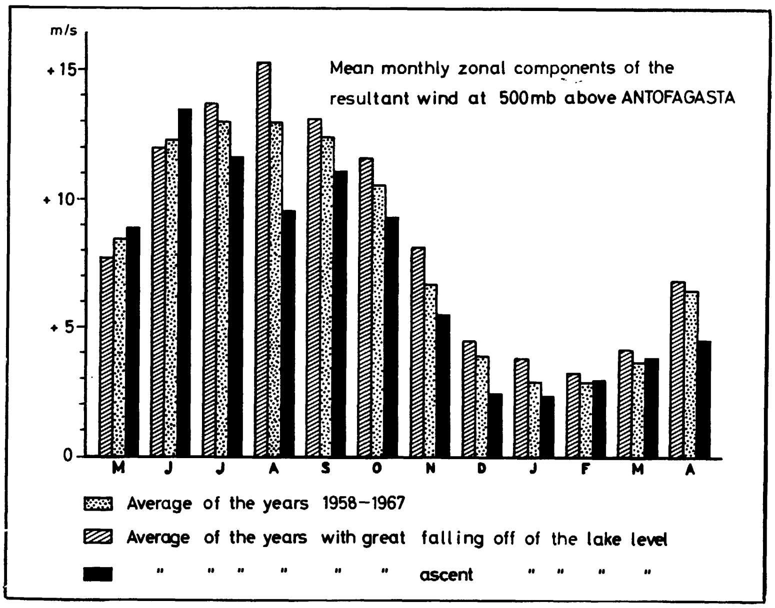

Figure 3. Mean monthly components of the resultant wind at 500 mb above Antofagasta.

RECENT CLIMATIC FLUCTUATIONS

The recent climatic variations on the Altiplano can best be illustrated using the fluctuations in the level of Lake Titicaca. The annual fluctuations of about 70 cm are superimposed by long-term alterations of

5 m. Examination of the water budget (Kessler 1974) showed that the long-term fluctuations of the level are due mainly to changes in precipitation onto the lake and the catchment area. Fluctuations in outflow through the Desaguadero River and lake evaporation are only of subordinate significance. The long-term fluctuations of Lake Titicaca can therefore be regarded as a good indicator for the changes in precipitation on the Altiplano.

In order to clarify the connection between recent circulation anomalies and fluctuations of precipitation, the monthly mean values of the zonal wind component at 500 mb above Antofagasta were examined from May 1958 to April 1967 and correlated with the level fluctuations of Lake Titicaca. As Fig. 3 shows, high westerly wind components resulted when the lake level decreased and low components resulted when the lake level increased (with the exception of May and June). In other words, during the increase of the belt of the westerlies and its displacement to the north, a deficit of the amount of precipitation occurred, and vice versa. These observations suggest that a similar shift of the circulation belts occurred in the Late Pleistocene during the Huancane II readvance and the formation of Lake Tauca.

In this context it should be mentioned that the considerable rise in the level of Lake Titicaca in 1973-1976 (Kessler 1981) occurred together with an increase in the snow cover on the land surfaces of the Northern Hemisphere and with a decrease in the sea ice cover on the Southern Hemisphere (Kukla 1981). This global asymmetry of the snow and ice cover and the simultaneous rise of the water level in Lake Titicaca can be seen qualitatively as a recent analogy to the Late Pleistocene Lake Tauca period.

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