Extended Abstract

Holocene climatic changes in the Bolivian Andes from wetland deposits in non-glacial valleys

Michel Servant [1], Simone Servant-Vildary [2]

[1] IRD, 32 Avenue Henri Varagnat, 93143 Bondy, France, [2] IRD-MNHN, Laboratoire de Géologie, 43 Rue Buffon, 75005 Paris, France.
mone@ mnhn.fr

Introduction

In the southern tropical Andes, between 15°S and 23°S, the water level changes, as evidenced in the lacustrine basins of the Altiplano during the Holocene, were previously interpreted as the result of the modifications of the summer monsoon rains. If this is true, the Holocene paleoclimates must be characterized, both during the dry and the wet periods by : (1) more abundant precipitation in the northern than in the southern Altiplano, as to day (2) essentially summer precipitation and (3) intense convective rains (if the vertical structure of the tropical troposphere has not drastically changed). Some of the available paleodata are in disagreement with first point. During the early Holocene, the water levels were higher than to day in the Altiplano of northern Chile (Geyh *et al*., 1999) and southern Bolivia (Sylvestre *et al*., 1999),but lower in the northern Bolivian Altiplano (Cross *et al*., 2000; Mourguiart *et al*., 1998) ; these data suggest wetter conditions in the south than in the north. During the mid Holocene, the northern Chile data from river deposits indicate a wetter climate than to day (Betancourt *et al*., 2000), while the lacustrine records show drier conditions in the same area. Similar drier conditions are also observed in the entire Bolivian Altiplano. The only available data concerning the second point were obtained from paleoecological studies suggesting that precipitation occurred mainly in the summer in northern Chile (Betancourt *et al*., 2000). Concerning point 3, the intensity of individual rains is still unknown for the past, because the lacustrine records do not give any information about this aspect of the climate. For this reason, we have focused our research on river deposits in non glacial valleys. These deposits, in addition to registering the water level variations in the river floor, also register the intensity of floods (controlled by the intensity of individual rains) and the seasonal variations of the water flow (directly controlled by the distribution of precipitation during the year)_(Servant and Fontes, 1984).

Location of study sites

Our study sites are located between 4300m and 3400m in elevation in non-glacial valleys (Figure 1). This type of valley is characterized by a longitudinal profile with a steep gradient and a small watershed. The rivers are fed by local precipitation. Presently, they are submitted to strong floods during the wet season, the bottom of the valleys is intensively eroded, the fine particles are drained off downstream. The bottom of the valleys dry up during the other periods of the year, except site X which is fed by groundwater discharge.

Material and Methods

Lithology

In all the sites studied, exposure of fluvial deposits was observed along the entire longitudinal profile. Under these conditions, field observations allow separating the metre- or hectometer-scale sedimentological structures (due to the small_ scale spatial complexity of the river flows) from the structures which appear on a larger scale e.g. the complete longitudinal profile, which reflects the river’s regime). Four groups of facies were distinguished :

Group 1 is composed of peats, spread along the entire longitudinal profile, both in the bottom and at the edge of the valleys. They reflect the permanence of humid environments. A possible discharge from the groundwater reservoirs to maintain humid conditions even during the dry season can be rejected because groundwater reservoirs are too small and too sensitive to the short-term variations in precipitation(except site X). Thus we assume that the peats indicate that the precipitation was well distributed throughout the year.

Group 2 is predominantly made up of stratified clays, silts, fine sands, and swampy paleosoils. The stratigraphical units which are characterized by these facies, are widespread. This type of deposits is interpreted as the result of a river regime without marked floods, under climatic conditions drier than those inducing group 1. It is interpreted as a consequence of the weak intensity of individual rains on the watershed.

Group 3: Coarse detritic elements are mixed with clays, silts and sands. This type of deposit is found at the foot of the slopes ; peats or silts are sometimes interbedded. This coarse material (colluvial deposits) is weakly reworked by run-off on the slopes.

Group 4: Coarse elements are the only constituent of this group. Unconformities are frequently observed below the coarse material. This type of deposit reflect strong floods and strong individual rains on the watershed. The modern equivalent of this group is observed in all the Bolivian Andes, both in the arid regions of the south and in the wetter regions of the north.

Diatoms

The fine river deposits have preserved an abundant diatom flora. Diatom assemblages were studied in Rio Baja (north of Salar de Uyuni); time resolution is less than 100 years. Species with different ecological affinities are mixed in the samples. The partition of the sequence of the diatom assemblages into several clusters was used for the demarcation of diatom zones which allow to evidence the general ecological trend. Ecological interpretations are based on a modern reference obtained from observations made on a large range of modern environments(Miskane, 1997; Servant-Vildary and Roux, 1990). We estimated the relative water level and salinity variations over time.

Datings

Radiocarbon dates were performed on bulk organic matter or on plant debris. According to the local context, we estimate that the ages are free of significant reservoir effect.

Results

Figure 2 shows an example of the Holocene stratigraphy in a non glacial valley (Oko Kuro) and Figure 3 the stratigraphical correlations between selected sites. We determined three main paleohydrological phases in the all studied sites.

Phase 3, dated ~10 000 yr BP to ~7500 yr BP (all ages are expressed in radiocarbon dates), corresponds to a river regime without marked floods. Above 4300 m in elevation, humid conditions were permanent as suggested by well-developed peats at all the sites, precipitation was well distributed throughout the year. Below 4300 m the peats are rare, suggesting that precipitation was lower.

Phase 2, ~7500 yr BP to ~1500 yr BP, is characterized in the southern Bolivian Andes by a continuous fine sedimentation indicating the absence of strong floods throughout the interval; rare lenticular peats may be interbedded in the upper part. In the northern Bolivian Andes, these accumulations were interrupted by several short erosion phases and coarse material, interpreted as the result of stormy rains on the watershed. Peat layers are frequently intercalated, mainly at the end of the phase; this alternation evidenced a strong instability of the river regime on a secular time scale.

Phase 1, after 1500 yr BP, is characterized by a completely different river regime from the regime of the two previous phases. The valleys were submitted to intense erosion. The water flows with strong floods were similar to what they are to day. Stormy precipitation predominated on the watershed.

The diatom assemblages clarifed the paleohydrological variations during phases 2 and 3. At Rio Baja, they confirmed that between ~10100 yr BP and 2300 yr BP, the silty units were deposited in a shallow aquatic environment colonized by a continuous vegetation cover. They also evidenced a general trend in the water level changes (Figure 4) : (1) between ~10 100 yr BP and ~7600 yr BP the water level progressively rose, (2) between ~7600 yr BP and ~5400 yr BP, the bottom of the valley was still covered by humid meadows, but the water level was lower, (3) between ~5400 yr BP and ~4800 yr BP, the water level increased. Subsequently, after ~4800 yr BP, it was affected by significant short-term variations.

The mixed saline and freshwater species in all the samples probably reflect an inter annual variability of the climate combined with the spatial complexity of the habitats in this type of environment. However, the freshwater species are dominant in most of the samples. Effects of evaporation are weak because the water time residence was probably too short, except for a few episodes (around 7400 yr BP, 5500 yr BP, and 4000 yr BP) (Figure).

Discussion

As evidenced by the variations in the water level in Lake Titicaca, it is now admitted that the early Holocene was drier than to day, the mid Holocene even drier, and the late Holocene episodically dry. Dryness was also expected in the non glacial valleys but all the data obtained from the river deposits attest that, on the contrary, the rivers never completely dried up. Confirmation is given by the diatoms which are continuously present between ~10,000 yr BP and ~2400 yr BP (Rio Baja) or ~1500yr BP (other sites). We explain this permanent humidity by the onset of peculiar climatic conditions. The precipitation was always of the non stormy type, suggesting a weak atmospheric convection, except for some short episodes in the northern Bolivian Andes. Precipitation was well distributed throughout the year, particularly during the periods when peats accumulated.

At present, the climate at the high altitudes of the Bolivian Andes is controlled by the alternation of two main atmospheric fluxes (Vuille, 1999): the NE monsoon flux, which generates convective precipitation (December-April) and the southern westerlies during the dry season (May-November). However, occasional precipitation occur during this dry season (mainly in July and August) in relation with short-term modifications in the structure of the westerlies.

The past peculiar climate, between ~10 000 and ~1 500 yr BP (non stormy precipitation, more or less well distributed throughout the year) can be explained by the combination of two atmospheric processes: (1) the monsoon was substantially strongly weakened and the Andes were potentially submitted to a dry climate ; (2) the westerlies were present all year long over the Bolivian Andes. Short-term modifications in the structure of these westerlies entailed episodic precipitation. During the early Holocene, the greater frequency of these precipitation associated with nebulosity obliterated the effect of the dryness due to the greatly reduced monsoon precipitation : the wetlands were well developed in the non glacial valleys; after a dry phase, lake Titicaca rose without reaching its present level (Ybert, 1992), the lake level was slightly higher than to day in the Uyuni-Coipasa basin (Sylvestre *et al*., 1999), the water level increased in Rio Baja, and the lacustrine highstand occurred in the Altiplano of northern Chile (Geyh *et al*., 1999). During the middle Holocene, the dryness related to reduced monsoon rains was no longer attenuated because of the lower frequency of this type of precipitation: lacustrine levels dropped in all the basins, peatlands disappeared in the southern Bolivian Andes, and the water level was low in Rio Baja. Some short wetter periods episodically occurred in the lake Titicaca watershed. During the late Holocene, a climate without stormy rains remained so until 1500 yr BP in the southern Bolivian Andes. Diatoms indicate short-term variations in the water flow in the Rio Baja. In the Lake Titicaca area, intensification of secular hydrologic variability is evidenced by rapid alternation of peats and silts in the river deposits. Moreover, episodes of stormy rains interrupted the deposition of the fine deposits in this area. They suggest an influence of the convective monsoon rains. Strong changes in the P-E balance occurred in the basin of Lake Titicaca as shown by large fluctuations in the water levels (Abbott et al., 1997). After 1500 yr BP, the summer monsoon system controlled the climate of the Bolivian Andes.

If this scenario is true, we can expect changes in the climate of the lowlands located east to the Andes in relation with the modifications of the atmospheric circulation in the middle and upper troposphere. To day, the climate of these regions is controlled both by the seasonal shift of the ITCZ and by frequent anticyclonic advections of southern polar air masses in the low troposphere. These advections entail strong drops in temperature and precipitation at the contact point between the warm tropical and the cold polar air masses. This type of polar advections is known in several other sub tropical regions in both hemispheres (Schultz *et al*., 1997; Leroux, 1996). According to Leroux, the anticyclonic cold air masses in the low tropical troposphere are associated with cyclonic waves in the westerlies in the mid troposphere. These two processes, respectively in the low and mid troposphere, are at the origin of the precipitation that occurs during the dry season at the sub tropical latitudes both in the highlands and the lowlands. In central Brazil, palynological data suggest that a drier climate than to day's predominated during the early Holocene period (Salgado-Labouriau, 1997) suggesting a weak influence of the ITCZ. But the dryness was locally attenuated by cold front precipitation; polar air mass advections were intense during this period, as suggested by low temperatures (Ledru *et al*., 1998). In the south eastern Amazonia, the wet climate evidenced during the early Holocene (Absy *et al*., 1991) was explained by precipitation related to the ITCZ (Martin *et al*., 1997). But another hypothesis may be proposed: this area could have been situated at the northern limit of the southern polar advections, giving way to precipitation. During the mid Holocene, the climate became drier in this area suggesting a weaker influence of the cold-front precipitation.

To be confirmed, this tentative scenario needs a detailed study of present atmospheric circulations in winter at the southern tropical latitudes of South America. In addition, a mesoscale climatic simulation is necessary.

References

Abbott , M. B., Binford, M.W., Brenner, M. and Kelts, K.R., 1997a. "A 3500 ^{14}C yr High-Resolution Record of Water-Level Changes in Lake Titicaca, Bolivia/Peru." Quaternary Research, 47:169-180.

Absy, M. L., Cleef, A., Fournier, M., Martin, L., Servant, M., Siffedine, A., Ferreira Da Silva, M., Soubiès, F., Suguio, K., Turcq, B., and van Der Hammen, T. (1991). Mise en évidence de quatre phases d'ouverture de la forêt dense dans le sud-est de l'Amazonie au cours des 60 000 dernières années. Première comparaison avec d'autres régions tropicales. *Comptes Rendus Académie Science, Paris,* 312, 673-678.

Betancourt, J. L., Latore, C., Rech, J. A., Quade, J., and Rylander, K. A. (2000). A 22, 000-Year Record of Monsoonal Precipitation from Northern Chile's Atacama Desert. *Science* 289, 1542-1546.

Cross, S. L., Baker, P. A., Seltzer, G. O., Fritz, S. C., and Dunbar, R. B. (2000). A new estimate of the Holocene lowstand level of Lake Titicaca, central Andes, and implications for tropical palaeohydrology. *The Holocene* 10, 21-32.

Geyh, M. A., Grosjean, M., Nunes, L., and Schotterer, U. (1999). Radiocarbon reservoir effect and the timing of the Late-Glacial/Early Holocene humid phase in the Atacama desert (Northern Chile). *Quaternary Research* 52, 143-153.

Ledru, M. P., Salgado-Labouriau, M. L., and Lorscheitter, M. L. (1998). Vegetation dynamics in southern and central Brazil during the last 10,000 yr B.P. *Review of Palaeobotany and Palynology* 99, 131-142.

Leroux, M. (1996). La dynamique du temps et du climat. Masson, Paris, 310 pp.

Martin, L., Bertaux, J., Corrège, T., Ledru, M. P., Mourguiart, P., Sifeddine, A., Soubiès, F., Wirrmann, D., Suguio, K., and Turcq, B. (1997). Astronomical forcing of contrasting rainfall changes in tropical South America between 12, 400 and 8, 800 cal yr BP. *Quaternary Research* 47, 117-122.

Miskane, N. (1997). "Les paléoenvironnements de haute montagne pendant l'Holocène récent d'après l'étude des diatomées actuelles et fossiles de deux vallées glaciaires de Bolivie. Implications paléoclimatiques." Unpublished PhD thesis, Muséum National Histoire Naturelle.Paris, 385 pp.

Mourguiart, P., Corrège, T., Wirrmann, D., Argollo, J., Pourchet, M., and Carbonnel, P. (1998). Holocene paleohydrology of lake Titicaca estimated from an ostracod- based transfer function. *Palaeogeography, Palaeoclimatology, Palaeoecology* 143, 51-72.

Salgado-Labouriau, M. L., Barberi, M., Ferraz-Vicentini, K.R., and Parizzi, M.G.,. (1997). A dry climatic event during the late Quaternary of tropical Brazil. *Review of Palaeobotany and Palynology,* 99, 115-129.

Schultz, D. M., Braxken, W. E., Bosart, L. F., Hakim, G. J., Bedrick, M. A., Dikinson, M. J., and Tyle, K. R. (1997). The 1993 Superstorm Cold Surge: Frontal Structure, Gap Flow, and Tropical Impact. *American Meteorological Society* 125, 5-39.

Servant, M., and Fontes, J. C. (1984). Les basses terrasses fluviatiles du Quaternaire récent des Andes boliviennes. *Cahiers ORSTOM, série Géologie,* 14, 15-28.

Servant-Vildary, S., and Roux, M. (1990). Multivariate analysis of diatoms and water chemistry in Bolivian saline lakes. *Hydrobiologia* 197, 267-290.

Sylvestre, F., Servant-Vildary, S., Servant, M., Causse, C., Fournier, M., and Ybert, J. P. (1999). Lake-level chronology on the Southern Bolivian Altiplano (18-23°S) during Late-Glacial Time and the Early Holocene. *Quaternary Research* 51, 54-66.

Vuille, M. (1999). Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the Southern Oscillation. *International Journal of Climatology* 19, 1579-1600.

Ybert, J. P. (1992). Ancient lake environments as deduced from pollen analysis. *In* "*Lake Titicaca, a synthesis of Limnological Knowledge*." (C. D. a. A. Iltis, Ed.), pp. 49-62. Kluwer Academic.

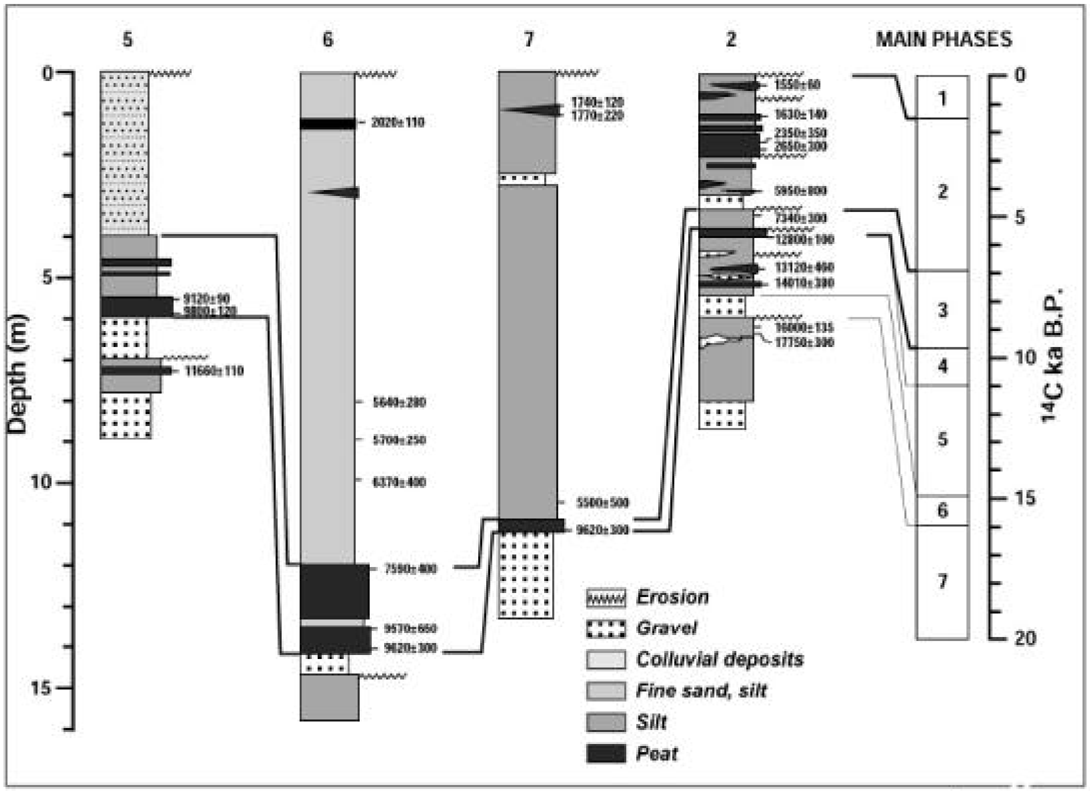
5
6
7
2
MAIN PHASES
Depth (m)
0
5
10
15
2020±110
1740±120
1770±220
1550±60
1630±140
2350±350
2650±300
5950±800
7340±300
12800±100
13120±400
14010±380
16000±135
17750±300
9120±90
11660±110
5640±280
5700±250
6370±400
5500±500
7550±400
9570±660
9620±300
1
2
3
4
5
6
7
20
^{14}C ka B.P.
Erosion
Gravel
Colluvial deposits
Fine sand, silt
Silt
Peat

Fig.

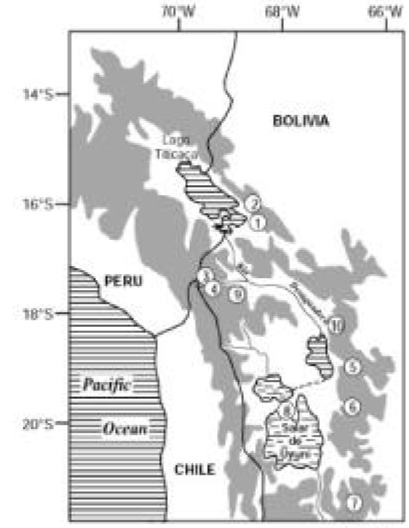
70°W
68°W
66°W
14°S
16°S
18°S
20°S
BOLIVIA
PERU
CHILE
Pacific
Ocean
Lago Titicaca
Salar de Uyuni

Fig. 1