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HOLOCENE ENVIRONMENTAL CHANGES IN THE ATACAMA ALTIPLANO AND PALEOCLIMATIC IMPLICATIONS

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Abstract

Strengthened summer monsoon brought tropical/continental moisture as far south as 25°S during late-glacial and early Holocene times. Precipitation rates in the Altiplano of the western Andes (24°S) increased to 500 mm yr^{-1} compared to <200 mm yr^{-1} today. There is evidence of dramatically decreasing lake levels between 8 400 and about 3 000 yr B.P., and conditions drier than today were established. This arid period was interrupted by low-frequency but heavy storms. The monsoon precipitation belt advanced once again in several stages to its current position (200 mm yr^{-1} isohyeta at 24°S) around 3 000 yr B.P. The reasons for these changes are not known: the variable circulation in the E-Pacific, teleconnections to the northern hemisphere, environmental changes in the source area of the moisture (*i.e.* tropical continent), or internal forcing due to changes in the radiation budget of the Altiplano are considered as possible explanations.

Key words: *Climatic changes, Monsoon, Northern Chile, Late-Glacial, Holocene.*

CAMBIOS MEDIOAMBIENTALES DURANTE EL HOLOCENO EN EL ALTIPLANO DE ATACAMA E IMPLICACIONES PALEOCLIMÁTICAS

Resumen

Estudios pluridisciplinarios han permitido reconstruir los cambios extremos en el balance hídrico experimentados en el Altiplano de Atacama durante el Holoceno. La intensificación del monzón de verano (*invierno boliviano*) aumentó la precipitación de origen continental en la región hasta los 25° S durante el Tardiglacial/Holoceno temprano. La precipitación en la región de los Andes occidentales (24° S) se incrementó hasta 500 mm por año en comparación con los 200 mm anuales de la actualidad. Durante el período entre 8 400 y 3 000 BP aproximadamente, la extrema aridez y la escasa precipitación

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dominada por tormentas muy intensas pero esporádicas fueron responsables de un descenso dramático del nivel de los lagos. A partir de los 3 000 a BP, el cinturón de lluvia tropical volvió a desplazarse hacia el norte en varias fases hasta su posición actual (isoyeta de 200 mm anuales a 24° S). Diversos factores se consideran para explicar esta evolución paleoclimática: teleconexiones con el hemisferio norte, cambios en la circulación oceánica en el Pacífico oriental, cambios ambientales en la cuenca amazónica donde se origina el vapor de agua, o diferencias en albedo y cubierta de nubes en la región de Atacama.

Palabras claves: *Cambios climáticos, Monzón, Norte de Chile, Tardiglacial, Holoceno.*

CHANGEMENTS DANS L'ENVIRONNEMENT HOLOCÈNE DE L'ALTIPLANO D'ATACAMA ET IMPLICATIONS PALÉOCLIMATIQUES

Résumé

Une mousson renforcée a transporté l'humidité continentale vers l'Altiplano chilien pendant le Tardiglaciaire et le début de l'Holocène. Les précipitations étaient de l'ordre de 500 mm par an, valeur à comparer aux moins de 200 mm actuels. Les conditions climatiques ont été plus arides que de nos jours entre 8 400 et 3 000 ans BP environ. À partir de cette dernière date, le climat moderne, caractérisé par une réintensification des pluies tropicales, s'est établi. Les raisons des changements du climat pendant l'Holocène sur l'Altiplano ne sont pas connues. Divers facteurs peuvent expliquer ces changements paléoclimatiques : des variations de la circulation dans l'Océan Pacifique, des téléconnexions avec l'hémisphère Nord ou bien avec les bàsses terres du Continent Américain, ou bien des changements dans le bilan radiatif sur l'Altiplano.

Mots-clés : *Changements climatiques, Mousson, Nord Chili, Tardiglaciaire, Holocène.*

INTRODUCTION

The Holocene is known as the most stable climatic period during the last 150,000 years (*e.g.* Lorius & Oeschger, 1994). This view is based on $\delta^{18}O$ records in the high-latitude ice cores from the northern and southern hemisphere, and refers mainly to temperature changes. New evidence from tropical areas balances this view of the 'stable' Holocene. Here, the changes reflect dramatic variations in the effective moisture regime. In the tropical areas of the northern hemisphere, the early Holocene pluvial is attributed to strengthened summer monsoon, primarily forced by increasing summer insolation (Kutzbach & Street-Perrott, 1985). Evidence for abrupt moisture changes during the last 10,000 years has also been found in the tropical part of the Central Andes, *i.e.* in the area of lake Titicaca and in the Bolivian/ Peruvian Andes (Martin *et al.*, 1993; Thompson *et al.*, 1985, and others), in Central Brazil (*e.g.* Ledru, 1993), and in the winter precipitation belt of Central Chile between 30°S and 32°S (Villagrán & Varela, 1990; Veit, 1994). It has been speculated that the ENSO played a major role in controlling the precipitation pattern in the tropical/subtropical Andes. However, little is known about the causes of such large-scale and long-term moisture changes, and the flickering switch of the Humboldt current in this area.

The Atacama Altiplano in Northern Chile (Fig. 1) is presently located in the extremely arid area where the tropical summer rainfall belt and the extratropical winter precipitation belt converge and sometimes overlap. The Altiplano between 19°S and 27°S is so arid that no glaciers can survive today. But this area is highly sensitive to changes in effective moisture, and is therefore one of the key sites for studying shifts and/or changing intensities of the tropical and westerly circulation belts, and thus for addressing the phenomenon of moisture changes in the tropical Andes during the Holocene.

Most of the paleoclimatic evidence from the Atacama Altiplano documents the spectacular late-glacial humid Tauca phase. The lake surfaces between 21-24°S increased dramatically and large freshwater bodies were established in the Altiplano between ca 15,000 to < 10,400 yr B.P. Energy and water budget models suggest that the precipitation rates increased up to 500 mm yr^{-1} compared to < 200 mm yr^{-1} today (Grosjean, 1994; Grosjean *et al.*, 1995). But little is known about the Holocene, since most lake sediments were destroyed. Other archives like glacial deposits were not datable, peat bogs did not cover the entire period of time, or the environmental changes had to be inferred from the history of human occupation and resource use (Grosjean & Nuñez, 1994).

First, we shall describe data from new archives that provide insight into the Holocene environmental conditions in the Atacama Altiplano. Secondly, we shall briefly discuss spatial relations with the environment in the surrounding areas. Thirdly, we shall review modern climatic patterns in order to find analogue situations that match spatially with the multi-proxy data set in the past. Can we explain past conditions by varying the statistical frequency of modern patterns? Finally, we shall speculate about the possible forcing mechanisms for the observed moisture changes during the late-glacial and Holocene period.

1. EVIDENCE FOR CHANGES DURING THE HOLOCENE

1. 1. The end of the humid Tauca phase

The end of the humid Tauca phase was the first major environmental change in the Holocene. Conventional radiocarbon ages on stromatolites, total C_{org} and carbonate fractions of laminated lake sediments were the only available data so far. It has been suggested that the high lake levels and the humid late-glacial climate persisted longer than 10,400 yr B.P. (Grosjean, 1994). Conditions as arid as those today were established around 8 400 yr B.P., leaving a rather long window of time open for the transition. This is partly due to difficulties

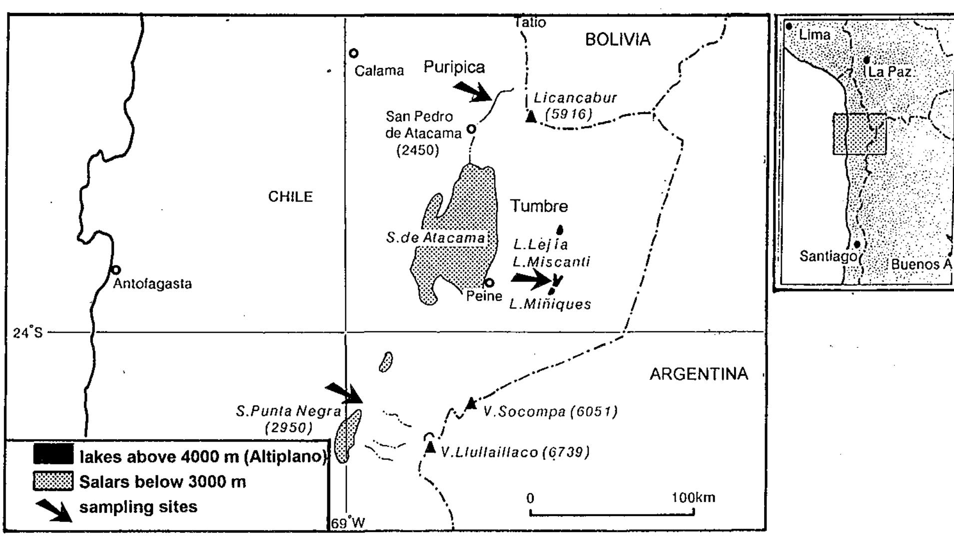

Fig. 1 - Map of the research area.

with the material we had to use for radiocarbon dating ('reservoir effect', see Grosjean *et al.*, 1995). New radiocarbon dates for peat in the Salar Punta Negra cover the period from 10,290 ± 90 yr B.P. ($\delta^{13}C$ = -25.5 ‰, Hv-19692), 9 885 ± 300 yr B.P. ($\delta^{13}C$= -26.5 ‰, Hv-19694) to 8 450 ± 765 yr B.P. ($\delta^{13}C$ = -27.2 ‰, Hv-19693; Messerli *et al.*, forthcoming). Our 120 cm deep sediment profile (Fig. 1, 24°25'S / 68°54'W, 2 980 m) consists of alternating beds with peat and shallow-water deposits (mainly diatomites and clay) suggesting ponds with open water, high river runoff from the Llullaillaco area, and generally quite humid conditions. The fact that such conditions reached far into the Holocene (as recent as 8 500 yr B.P.) makes the period of transition from the humid 'Tauca mode' to the fully arid 'mid Holocene mode' of the climate rather short, and abrupt changes are likely to have taken place. This finding would strongly support the hypothesis that the regional hiatus in human occupation (*Silencio Arqueológico*) between 8 500 to 4 800 yr B.P. was initiated by a dramatic decrease in resources due to arid climatic conditions (Grosjean & Nuñez, 1994). However, the time shortly before 8 200 yr B.P. seems to be an increasingly important date for the world climate (*e.g.* Schotterer & Oeschger, 1994).

1. 2. Mid Holocene aridity and floods

Multi-proxy data for the extremely arid mid Holocene period (8 400 to around 3 000 yr B.P.) are scarce. The lake levels were extremely low, most basins were completely dry, and the sediments were eroded by wind and destroyed. The sediment and pollen profile in Tumbre (Graf, 1992) is the only available archive so far. We found a sandy matrix low in organic matter for the time between 7 500 to 3 900 yr B.P. Peat becomes dominant after 3 900 yr B.P. New lake sediment data from Laguna Miscanti and fluvio-lacustrine sediments in the Quebrada Puripica give a detailed record of environmental and climatic conditions for the mid Holocene time (Fig. 1 and 2).

The accumulation of mid Holocene fluvio-lacustrine sediments in the Puripica valley is interpreted as evidence of increasing aridity, when the vegetation cover was poor, erosion control was very weak, and rainfall was highly variable. The sediments provide evidence of low-frequency, heavy storms (return period about 1 000 to 500 years) at 5 080 yr B.P., shortly prior to 3 800 yr B.P. and around 3 300 yr B.P. Three periods of sedimentation are distinguished. Between 6 200 and 5 100 yr B.P., there are no indicators of big torrential events. Fluvial sand and lacustrine deposits were dominant. The accumulation of sediments and the lack of erosive surfaces suggest low levels of free energy in the river. This would be characteristic for a generally arid climate with minor episodic storms, when debris flows plugged the river course and gave rise to short-term lacustrine sedimentation. The storm activity was at a maximum between 5 100 and 3 800 yr B.P.: sediments of torrential events were dominant, fluvial sand and lake deposits were scarce. We identified sediments of at least 12 small storms (maximum size of particles 10 cm), more than 20 moderate (particles 10-20 cm) and 2-4 big storms (particles > 20 cm). The general environmental conditions probably reached the peak of aridity during this time period. Between 3 800 and 3 100 yr B.P., the lacustrine deposits became dominant, although interrupted by episodic torrential events (small, moderate and one big storm). Generally dry conditions with sediment accumulation prevailed until 3 100 yr B.P. Although the number and the frequency of the events listed here are purposely conservative and probably underestimated, they give an idea about dramatic floods and morphodynamics in an extremely arid environment.

Further evidence of conditions much drier than those today was found in mid Holocene erosive surfaces and the facies with subaerial exposure in the sediments of Laguna Miscanti (Fig. 2), suggesting a lake level up to 10 m lower than today (Valero-Garcés *et al.*, forthcoming).

1. 3. The establishment of the modern climate

The transition from mid-Holocene extremely dry conditions to a modern slightly more humid climate with less than 200 mm yr^{-1} precipitation is best seen in the sediments of Laguna Miscanti (Valero-Garcés *et al.*, forthcoming, Fig. 2).

The lake sediments at depths between 180 and 145 cm show the change from a shallow, highly saline, and aragonite precipitating environment to modern conditions with a 9 m-deep, relatively freshwater environment (6.4 mS cm^{-1}), magnesian calcite precipitation, and abundant diatom opal. We emphasize the 'flickering switch'-nature of this transition, suggesting that the changes in the lake were probably forced by several moisture impulses back and forth, and were not due to a steady one-way vector. The timing of this transition in the sediments of Laguna Miscanti is uncertain. Given the current stage of knowledge, we interpret the transitions as synchronous to the mid to late Holocene transition in the Quebrada Puripica. There, the milieu in the river switched from the mid Holocene

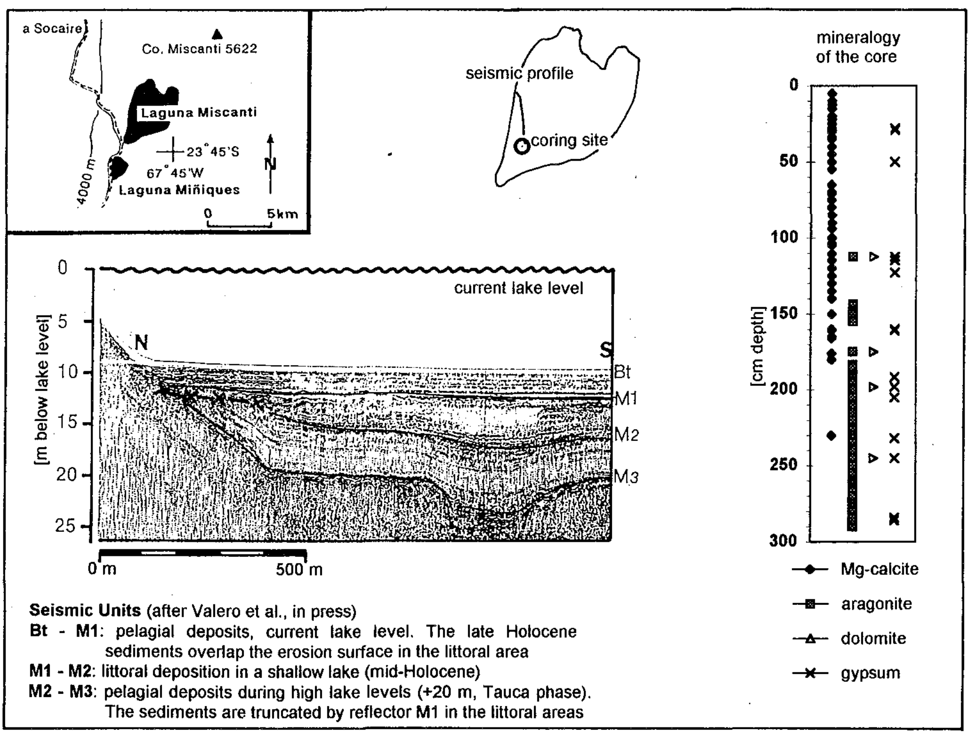

Fig. 2 - Seismic profile and mineralogy of the sediment core of Laguna Miscanti. The core reached with the lower section the seismic unit M1-M2.

accumulation mode (fully arid climate) to the late Holocene erosion mode (somewhat more humid) shortly after 3 110 ± 70 yr B.P. (Beta-63361). This in turn is interpreted as a significant change in the hydrological regime of the river: we suggest higher runoff, better erosion control on the adjacent slopes due to denser vegetation, higher free energy in the river, and consequently, linear erosion in the river bed. A generally more humid climate with modern rainfall (< 200 mm yr^{-1}) and a somewhat smoother precipitation regime is postulated. However, the erosive potential of the Rio Puripica is surprising: more than 16 m of sediments were cut through within the last 2 000 years. Obviously, a remarkable amount of water was required, and we can speculate if the current precipitation and runoff would be sufficient.

2. THE SPATIAL PATTERN OF THE HOLOCENE CLIMATIC CHANGES

The Holocene climatic history from three different areas at different latitudes along the Andes is shown in figure 3: the area of Lake Titicaca at 16°S in the tropical precipitation regime (Martin *et al.*, 1993), the Atacama Altiplano at 24 °S in the arid zone, and the coastal area of Central Chile at 32°S in the westerly winter rainfall belt (Villagrán & Varela, 1990).

The Atacama Altiplano at 24°S shows an environmental history similar to that in the tropical area of Lake Titicaca. The preliminary results show that completely arid conditions were established slightly earlier in the Atacama Altiplano at 24°S than at 16°S, while the switch from the most arid mid Holocene to a modern climate was probably somewhat later

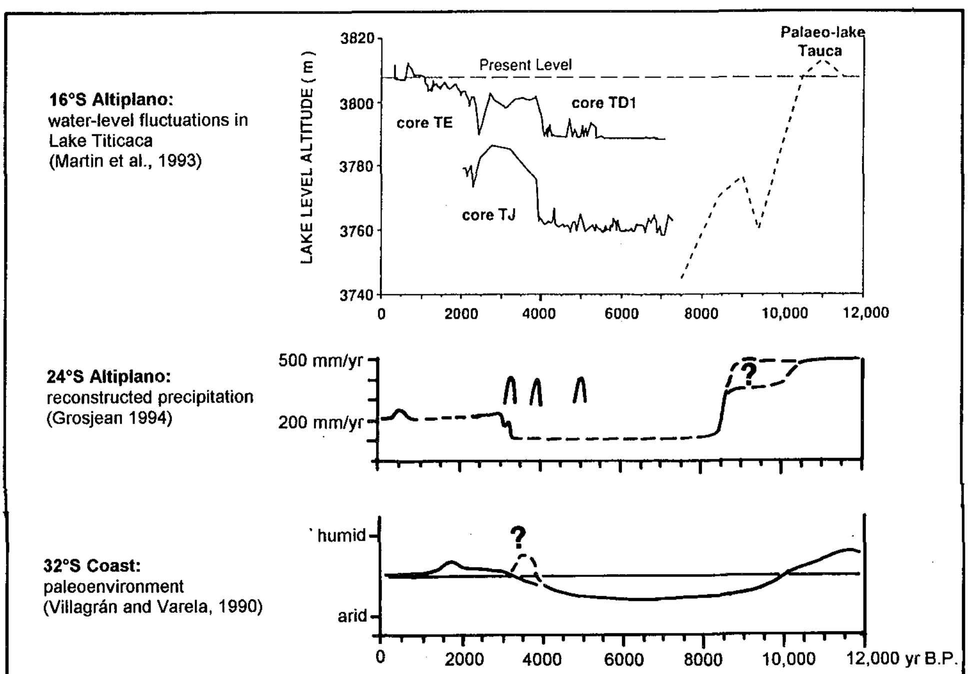

Fig. 3 - Moisture changes in the Altiplano at 16°S, at 24°S and on the Chilean coast at 32°S during the last 12,000 yr B.P.

at 24°S than in the Titicaca basin. It is suggested that receding and re-advancing tropical moisture would explain such a humidity pattern. However, the mechanisms and the timing have yet to be better documented. The increase in aridity in the winter rainfall area at 32° around 10,000 yr B.P. occurred some 2 000 years earlier than in the tropical areas (Villagrán & Varela, 1990). Therefore, this seems to be a phenomenon of the termination of the Pleistocene, related to poleward shifts in the westerly circulation belt. The increase in moisture around 3 000 yr B.P. is synchronous with what happened at 24°S. The same effect was also found in the Argentinean Andes between 32-35°S (Markgraf, 1983).

3. THE MODERN PRECIPITATION PATTERN: A USEFUL ANALOGUE?

The current precipitation pattern will be briefly reviewed in order to evaluate potential mechanisms for explaining the moisture changes in the Atacama Altiplano at 24°S. There are three mechanisms to transport moisture into this area: i) frontal rain from the westerly circulation, mainly during winter; ii) tropical summer rainfall (invierno Boliviano, summer monsoon), here usually related to a high-elevation anticyclonic flow pattern; and iii) drops of cold polar air masses (cut-offs) that travel into low-latitude areas, collide with warm/moist tropical air, and trigger precipitation during winter, spring and fall (Fuenzalida & Rutllant, 1986; Messerli *et al.*, forthcoming). Cut-off events activate precipitation in isolated cells in low-latitude areas, and the precipitation of the analyzed case studies showed a continental isotopic signal.

Frontal winter rain from the westerlies does not match the paleoenvironmental data set for the late-glacial/early Holocene Tauca phase in the Atacama at 24°S. A southward increase in the precipitation rates would be expected, but this contrasts with the N-S moisture gradients as inferred from equilibrium lines of former glaciations and late-glacial lake deposits between 18° and 29°S (Messerli *et al.*, 1993; Messerli *et al.*, forthcoming). Increased winter precipitation would also suggest environmental changes in the lower elevation areas towards the coast of the Atacama desert. According to our current knowledge, the paleodata indicate that the moisture changes happened exclusively in the high elevation areas in the Altiplano while fully arid conditions prevailed in the lower elevation areas.

Increased tropical summer precipitation matches the paleoenvironmental data set for the late-glacial/early Holocene time: the expected northward increase in moisture is observed in the gradient of former lake levels and equilibrium lines of reconstructed glaciers in this area (Messerli *et al.*, forthcoming). However, synchroneity of the maximum glaciation in this area with the Tauca phase is most likely, but could not yet be documented. The humid Tauca phase hit exclusively the higher elevation areas in the Andes, while the low elevation areas below 3 500 m were touched by higher runoff at most. This situation is typical for summer precipitation, giving additional evidence that strengthened summer monsoon played the major role during that period of time. Given the stage of knowledge about current climatic conditions, the tropical continent is the dominant source for moisture (Aravena *et al.*, 1989; Grosjean *et al.*, 1995). In this sense, the modern summer precipitation pattern, although intensified, could be an analogous model for early Holocene circulation as well. The continental origin of the moisture further implies that we would have to consider changing moisture regimes in the source area of the water vapor to explain varying moisture transport into the Atacama Altiplano. Indeed, the environmental history of the tropical low-lands (*e.g.*

in Central Brazil; Ledru, 1993) strikingly matches the environmental changes in the Altiplano. It follows that we emphasize the role of past vegetation cover, runoff regimes and evapotranspiration rates (i.e. recycling of the water vapor) in continental South America in order to explain past moisture changes in the Atacama Altiplano.

The cut-off events are interesting synoptic features and deserve close consideration. The drops of NE traveling polar air masses trigger precipitation in the tropical areas when colliding with warm/humid air, while dry conditions persist in the subtropical areas to the south. This synoptic pattern would match the N-S moisture gradients as found in the paleodata (Messerli *et al.*, forthcoming). However, little is known about the statistical significance and the frequency of such events. The Tauca phase climate was most likely quite stable on a centennial scale with regard to precipitation (Grosjean *et al.*, 1995), and it is not known if cut-offs could provide the Altiplano with such a smooth, constant and low-variability precipitation supply. But superimposed on the tropical summer precipitation, they may play a major role in some areas. We speculate that the low-frequency heavy storms found in the mid-Holocene section of Quebrada Puripica might have been triggered by such cut-off events.

We conclude that strengthened summer monsoon brought tropical/continental moisture as far south as 24°S during late-glacial and early Holocene times. The tropical precipitation belt (*e.g.* the 400 mm yr^{-1} isohyeta) retreated around 8 400 yr B.P. from 24°S to further north than 16°S (Lake Titicaca), giving rise to a pronounced arid period in the Atacama Altiplano during mid Holocene times. The transition took place probably within a short time and led to a dramatic drop in the lake levels and to an abrupt establishment of completely dry conditions. This arid period was interrupted by low-frequency but heavy storms. The monsoonal precipitation belt re-advanced in several steps back and forth to its current position around 3 000 yr B.P. We found no evidence so far that westerly frontal precipitation played a dominant role north of 29°S during the last 10,000 years. However, we must still allow for the possibility of surprises that are well documented with field data.

5. UNANSWERED QUESTIONS

What forced the monsoonal precipitation belt to move back and forth in the Atacama Altiplano? External and internal mechanisms or even a combination of both are under consideration, though the answer is not known so far.

The Milancovitch parameters are believed to have strengthened the summer monsoon in the northern hemisphere tropical areas during early Holocene times (Kutzbach & Street-Perrott, 1985). In contrast to the northern hemisphere, summer insolation was minimal in the low-latitude areas of the southern hemisphere during this period of time. We found evidence that the Tauca phase lasted longer into the early Holocene than had previously been believed, and might, therefore, be related to some extent to the early Holocene pluvial in tropical areas of the northern hemisphere. A teleconnection to the northern branch of the tropical Hadley cell might be considered, at least for a limited period of time.

A second kind of external forcing might be found in the ocean circulation along the South American coast. Since the early Holocene SE Pacific was warmer than today (Rollins *et al.*, 1986), the SE Pacific anticyclone was likely destabilized and ultimately less powerful in its moisture-blocking effect. Villagrán & Varela (1990) concluded that the increasing influence of the SE Pacific anticyclone caused mid Holocene arid conditions in Central Chile.

We must also consider internal forcing of the Tauca phase paleomonsoon due to variations of the surface characteristics and due to changes in the radiation budget of the Altiplano itself. Large-scale reduction of surface albedo is expected due to larger surfaces of the former lakes (albedo white salt pan = 0.7, lake = 0.1), while significantly larger glacier surfaces and snow cover at the same time would markedly increase the overall albedo of a certain area. The net difference in surface albedo between the positive and negative effects has yet to be evaluated in case study areas, where the paleoenvironmental changes in time are well known.

All three arguments - the variable ocean, the teleconnection with the northern hemisphere and the continental lowlands in South America, and the internal changes in surface characteristics - are worth debating, since they all provide a framework for rapid changes (Lorius & Oeschger, 1994; Street-Perrott, 1994). However, one of the most variable and powerful elements of the radiation budget, and thus of climate, is the clouds. Grosjean (1994) pointed to the high sensitivity of the water budget in the Altiplano with respect to cloud cover. Cess *et al.* (1995) impressively demonstrate that the traditional working assumptions for the radiation budget of clouds have to be revised. And paleo-cloudiness? All we know is that it is very important, and we cannot deal with it.

Acknowledgments

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References Cited

ARAVENA, R., PEÑA, H., GRILLI, A., SUZUKI, O. & MORDECKAI, M., 1989 - Evolución isotópica de las lluvias y origen de las masas de aire en el Altiplano chileno. *IAEA-TECDOC*, **502**: 129-142.

CESS, R.D., ZHANG, M.H., MINNIS, P., CORSETTI, L., DUTTON, E.G., FORGAN, B.W., GARBER, D.P., GATES, W.L., HACK, J.J., HARRISON, E.F., JING, X., KIEHL, J.T., LONG, C.N., MORCRETTE J.-J., POTTER, G.L., RAMANATHAN, V., SUBASILAR, B., WHITLOCK, C.H., YOUNG, D.F, & ZHOU, Y., 1995 - Absorbtion of Solar Radiation by Clouds: Observations versus Models. *Science*, **267**: 496-503.

FUENZALIDA, H. & RUTLLANT, J., 1986 - Estudio sobre el origen del vapor de agua que precipita en el invierno altiplánico. Informe final, 51p., Santiago: Universidad de Chile.

GRAF, K., 1992 - Pollendiagramme aus den Anden. Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. *Physische Geographie*, **34**: 1-138.

GROSJEAN, M., 1994 - Paleohydrology of Laguna Letia (North Chilean Altiplano and Climatic Implications for Late-glacial Times). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **109**: 89-100.

GROSJEAN, M. & NUÑEZ, L., 1994 - Lateglacial, Early and Middle Holocene Environments, Human Occupation and Resource Use in the Atacama (Northern Chile). *Geoarchaeology*, **9**: 271-286.

GROSJEAN, M., GEYH, M.A., MESSERLI, B. & SCHOTTERER, U., 1995 - Late-glacial and early Holocene lake sediments, groundwater formation and climate in the Atacama Altiplano 22-24°S. *Journal of Paleolimnology*, **14**: 241-252.

KUTZBACH, J.E. & STREET-PERROT, F.A., 1985 - Milankovitch forcing of fluctuations in the level of tropical lakes from 18 to 0 kyr BP. *Nature*, **317**: 130-134.

LEDRU, M.-P., 1993 - Late Quaternary Environmental and Climatic Changes in Central Brazil. *Quaternary Research*, **39**: 90-98.

LORIUS, C. & OESCHGER, H., 1994 - Paleo-perspectives: Reducing Uncertainties in Global Change. *Ambio*, **23/1**: 30-36.

MARKGRAF, V., 1983 - Late and postglacial vegetational and paleoclimatic changes in subantarctic, temperate, and arid environments in Argentina. *Palynology*, **7**: 43-70.

MARTIN, L., FOURNIER, M., MOURGUIART, P., SIFEDDINE, A., TURCQ, B., ABSY, M.L. & FLEXOR, J-M., 1993 - Southern Oscillation Signals in South American Paleoclimatic Data of the Last 7000 Years. *Quaternary Research*, **39**: 338-346.

MESSERLI, B., GROSJEAN, M., BONANI, G., BÜRGI, A., GEYH, M.A., GRAF, K., RAMSEYER, K., ROMERO, H., SCHOTTERER, U., SCHREIER, H. & VUILLE, M., 1993 - Climate Change and Dynamics of Natural Resources in the Altiplano of Northern Chile during Late Glacial and Holocene Time. First Synthesis. *Mountain Research and Development*, **13(2)**: 117-127.

MESSERLI, B., AMMANN, C., GEYH, M.A., GROSJEAN, M., JENNY, B., KAMMER, K., & VUILLE, M., forthcoming - Current precipitation, late Pleistocene snow line, and lake level changes in the Atacama Altiplano (18°S - 28°30'S): the problem of the "Andean Dry Diagonal". *Bamberger Geographische Schriften*.

ROLLINS, H.B.III, RICHARDSON, J.B. & SANDWEISS, D.H., 1986 - The birth of El Nino: Geoarchaeological evidence and implications. *Geoarchaeology*, **1**: 17-28.

SCHOTTERER, U. & OESCHGER, H., 1994 - The Stability of the Climate System in Light of Recent Ice Core Measurements. *in: Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change* (N. Nakicenovic *et al.* eds.): 75-86; Laxenburg: IIASA.

STREET-PERROTT, F.A., 1994 - Paleo-perspectives: Changes in Terrestrial Ecosystems. *Ambio*, **23/1**: 37-43.

THOMPSON, L.G., MOSLEY-THOMPSON, E.P., BOLZAN, J.F. & KOCI, B.R., 1985 - A 1500 year record of tropical precipitation recorded in ice cores from the Quelccaya ice cap, Peru. *Science*, **229**: 971-973.

VALERO-GARCÉS, B., GROSJEAN, M. SCHWALB, A., GEYH, M.A., MESSERLI, B., & KELTS, K., forthcoming - Late Holocene environmental Change in the Atacama Altiplano: Limnogeology of Laguna Miscanti, Chile. *Journal of Paleolimnology*.

VEIT, H., 1994 - *Jungquartäre Landschafts- und Klimaentwicklung am Südrand der Atacama (Norte Chico, Chile)*, 261p., Bayreuth: University of Bayreuth.

VILLAGRÁN, C. & VARELA, J., 1990 - Palynological Evidence for Increased Aridity on the Central Chilean Coast during the Holocene. *Quaternary Research*, **34**: 198-207.