Late Quaternary history of the Atacama Desert

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Among the major subtropical deserts found in the Southern Hemisphere, the Atacama Desert is the driest. Throughout the Quaternary, the most pervasive climatic influence on the desert has been millennial-scale changes in the frequency and seasonality of the scant rainfall, and associated shifts in plant and animal distributions with elevation along the eastern margin of the desert. Over the past six years, we have mapped modern vegetation gradients and developed a number of palaeoenvironmental records, including vegetation histories from fossil rodent middens, ground-water levels from wetland (spring) deposits, and lake levels from shoreline evidence, along a 1200-km transect (16-26°S) in the Atacama Desert. A strength of this palaeoclimate transect has been the ability to apply the same methodologies across broad elevational, latitudinal, climatic, vegetation and hydrological gradients. We are using this palaeoclimate transect to reconstruct the histories of key components of the South American tropical (summer) and extratropical (winter) rainfall belts, precisely at those elevations where average annual rainfall wanes to zero. The focus has been on the transition from sparse, shrubby vegetation (known as the *Prepuna*) into *absolute desert*, an expansive hyperarid terrain that extends from just above the coastal fog zone (~800 m) to more than 3500 m in the most arid sectors in the southern Atacama.

One of the novel aspects of our study focuses on rodent middens, a unique paleoecological technique developed in the arid southwest of the United States (Betancourt et al., 1990). Rodent middens are amalgamations of plant remains (including seeds, flowers, leaves and wood), bones, insects, feathers and rodent feces all glued together within a crystallized matrix of rodent urine. In arid climates, they can survive for thousands of years underneath rock slabs and within crevices and caves. Midden plant remains are from within the rodent's foraging range (usually 200 m or less) and include plants collected for consumption, nest building and protection. In the Atacama, middens are produced by at least four different rodent families: Abrocomidae (*Abrocoma cinerea*, “chinchilla rats”); Chinchillidae (*Lagidium viscacia* and *Lagidium peruanum*, “vizcachas”); Muridae (*Phyllotis* spp. “leaf-eared mice”) and Octodontidae (*Octodontomys gliroides*, “brush-tailed rat”) (Fig. 1). Modern studies of *Phyllotis*, *Lagidium* and *Abrocoma* indicate that they are dietary generalists and probably not selective enough to introduce large biases into the midden record (Pearson, 1948; Pizzimenti and DeSalle, 1980; Cortés et al., 2002).

Climatic controls

The Atacama extends along the Pacific Andean slope from the southern border of Peru (18°S) to Copiapó, Chile (27°S). The region's hyperaridity is due to a combination of the extreme rainshadow of the high Andes, which blocks the advection of tropical/subtropical moisture from the east; the blocking influence of the semi-permanent South Pacific Anticyclone, which limits the influence of winter storm tracks from the south; and the generation of a temperature inversion at ~1000 m by the cold, north-flowing Humboldt Current, which constrains inland (upslope) penetration of Pacific moisture.

The South Pacific Anticyclone has been anchored against the westward bend in the South American continent throughout the late Tertiary. Uplift of the central Andes to their current elevation may have occurred as early as 15 million years ago (Ma) (Alpers and Brimhall, 1988; Vandervoot et al., 1995), although paleobotanical evidence suggests that the central Andes were only at half their modern elevation at 10 Ma (Gregory-Wodzicki, 2000). The Humboldt Current is thought to have been active since the early Tertiary (Keller et al., 1997), but may have reached its present intensity during the major expansion of the Antarctic ice sheet between 15-12.5 Ma (Flower and Kennett, 1993), or after the Central American Seaway closed between 3.5 and 3.0 Ma (Ibaraki, 1997).

Seasonal and annual precipitation totals in the region are determined by the number of precipitation days, and associated circulation anomalies during those days. Precipitation variability in both summer and winter is modulated primarily by Pacific SST (sea surface temperature) gradients and associated upper-air circulation anomalies (Vuille et al., 2000; Garreaud et al., 2003). These anomalies promote either greater spillover of summer moisture either from the Amazon to the northeast or the Gran Chaco to the southeast, or conversely, greater penetration of winter storm tracks from the southwest.

The recent flurry of palaeoclimate research in the wider central Andes region stems from interest about leads and lags between low and high latitudes, and the role of the tropics in global change at millennial to glacial-interglacial scales. Are variations in summer rainfall over the region just a function of minor seasonal variations in regional insolation, and their impact on the Bolivian High, or is the intensity of South American summer monsoon forced instead by changes in Pacific SST gradients with both tropical and extratropical teleconnections? A diverse array of records of continental climate change is now available to test these ideas. Notable among these are lake and salt cores from Lake Titicaca and Salar de Uyuni, chrono-stratigraphic work on shoreline deposits throughout the Altiplano, ice cores from Nevado Sajama and Illimani, salt cores from Salar de Atacama and Hombre Muerto and a lake core from Laguna Miscanti.

The northern Atacama Desert (16-21°S)

The northern portion of the Atacama Desert runs from Arequipa, in southern Peru (~16°S), to the north rim of the Río Loa catchment in northern Chile (~21°S). Characterized by abrupt relief, the northern Atacama is defined by a narrow and steep-sloping stretch between the Andes and the Pacific Ocean, with extensive wall canyons over 1 km in depth. Less than 100 km separate the Pacific Coast and Andean peaks over 6 km in height.

The rodent midden record described here comes from the vicinity of Arequipa, the second largest city in Peru nestled in the foothills of the western cordillera. Here, absolute desert grades into desert *Matorral* at ~2400 m of elevation, characterized by columnar cacti and xerophytic shrubs as well as small herbs and annual grasses. Plant cover increases dramatically above 2600 m but greater diversity occurs starting at 2800 m, with a mixture of *Matorral* (shrubs) and *Pajonal* (grassland) species.

The Arequipa record, described in Holmgren et al (2001), incorporates middens found between 2350 and 2850 m of elevation and collated into two main elevational bands below and above 2600 m. The majority of the middens were made by leaf-eared mice and chinchilla rats although a few were also made by mountain vizcachas. Overall, the Arequipa midden record is remarkably stable over the last 9,500 calendar years before 1950 (or BP— all ages are radiocarbon ages converted into calendar years) (Fig. 2a and b). At lower elevations, middens between 9.5 and 7.4 thousand years BP have remarkably low numbers of annuals, grasses and perennials as well as a low total number of taxa (10 and under). These taxa experience a threefold increase at 6,700 years BP, with annuals increasing from three to nine taxa, and the total number of taxa rising to 26. Other mid-Holocene middens are also characterized by a rich assemblage of annuals until 3,800 years BP. Middens from the late Holocene date between 1,300 years BP and the present and are slightly poorer in annuals and perennials when compared to mid-Holocene ones. The numbers of cacti remain surprisingly constant throughout the record, diminishing only slightly in the early Holocene.

Middens above 2600 m show somewhat greater vegetation stability. Most of the middens have between 15 and 20 taxa. Those dated between 4.0 and 3.4 thousand years BP, however, have fewer grasses and only 10 to 11 taxa. Middens younger than 700 years BP have the largest numbers of annuals and perennials. Cacti again remain remarkably constant. Of note in this series is the presence of *Stipa ichu* (a steppe grass) and *Opuntia ignescens* (a cushion cactus) between 5.0-4.5 thousand years BP. Both species now occur 450 and 750 m higher than the midden sites.

Other late Quaternary records from the northern Atacama generated by our research include Holocene lake level changes at Lago Aricota in southern Peru (17°22'S) and ground-water fluctuations recorded in terraced spring deposits throughout northernmost Chile. Radiocarbon dates of shoreline deposits at Lago Aricota indicate a maximum highstand (> 8m above the pre-dam 1955 lake level) between >7.1- 2.8 thousand years BP with a minor highstand dated to 1.7-1.3 thousand years BP (Placzek et al., 2001). Fossil spring and wetland deposits, which are located around modern springs and wetlands, are common surficial deposits in the Atacama Desert. These deposits generally consist of alluvial silt and sand, diatomite, organic mats, and tufa. Wetland deposits from four separate hydrologic settings were studied to reconstruct fluctuations in the height of local water tables: Zapahuira Springs (18.3°S, 3500 m) - a small point-source spring; Quebrada la Higuera (18.6°S, 3500 m) - a high-elevation drainage with isolated wetlands; Quebrada

Tana (19.5°S, 1200 m) - a low-elevation drainage that flows into the Pacific; Quebrada Guataguata (20.1°S, 2050 m) – a low-elevation drainage with isolated wetlands (Rech et al., 2001). We identified the following time-stratigraphic units of palaeowetland deposits indicating periods of elevated ground-water tables: Unit B (>13.8-10.2 thousand years B.P.) represents the highest episode of local water tables, Unit C (>5.9-4.8 thousand years B.P. and a second episode dating from 4.8-2.8 thousand years B.P.), and Unit D, composed of several episodes of deposits that are <3000 years old. The units are separated by episodes of fluvial downcutting, which occurs when the water table drops causing desiccation of these fine-grained sediments and subsequent erosion.

In summary, these records indicate episodes of increased effective moisture throughout the northern Atacama. Wet conditions were prominent during the late glacial period (14-10 thousand years BP) as implied by the palaeowetland record. Slightly more arid conditions occurred during the early Holocene, followed by a wetter episode during the middle Holocene (especially between ~7 to 4.5 thousand years BP), and a slightly drier late Holocene, punctuated by minor precipitation increases between 1-2 thousand years BP. These results, however, are largely at odds with other published records from high Andean lake records in the Peru/Bolivian Altiplano (discussed later).

The central Atacama Desert (21-24°S)

Among the salient features of the central Atacama are two pronounced embayments in the Andes cordillera, the Calama and Salar de Atacama basins, and the only perennial river to actually reach the Pacific Ocean, the Río Loa. Inland extension of the absolute desert is here much greater than in the northern Atacama, reaching elevations of 2900-3100 m and up to 300 km from the coast. An older mountain range, the Cordillera Domeyko, has its origins in this sector and runs parallel along the western Andean front into the southern Atacama. Here, plant diversity and distribution is tightly linked to mean annual precipitation, which increases from almost ~0 mm/year at ~2400 m to 200 mm/year at 4000 m. Along the Andean slope, a sparse vegetation of shrubs and small herbs, known as the *Prepuna*, appears at 2900 m and gradually transitions into the *Puna* (locally called *Tolar*) vegetation belt. The Puna belt, between 3100-3900 m, is dominated by shrubs of the

Asteraceae and Solanaceae with numerous summer annuals and columnar cacti. High Andean grassland dominated by tussock grasses such as *Stipa*, *Nassella* and *Festuca* is found above 3900 m. A more heterogenous mix of vegetation occurs along the Cordillera Domeyko, with impoverished *Stipa* grassland found above 3400 m and slightly wetter conditions on the east facing slopes with Tolar shrubs extending down to 3100 m. These same shrubs occur >3200 m on the drier west facing slopes.

We collected rodent middens from two major areas in the central Atacama. The first area is in the prepuna along the west- and east-facing slopes of the northern Cordillera Domeyko, between 3100-3300 m of elevation. The other midden area is along an escarpment of volcanic rocks at the southern portion of the Salar de Atacama, known as Tilocalar (between 2400-3050 m), an area now mostly devoid of all but the most drought-resistant plants (for more details see Betancourt et al., 2000; Latorre et al., 2002; 2003).

The Tilocalar series (44 middens) records vegetation invasions into what is now absolute desert over the last 45,000 years (summarized in Fig. 2c). Major wet phases, indicated by >30% extralocal plants (species not found in the area today), presence of steppe (some grass species present are found ~900 m above the localities today) and Tolar (Puna) shrubs as well as summer annuals and columnar cacti, occurred sometime before 44,000 years BP, and between 16.2-10 thousand years BP. Minor pulses of increased precipitation occurred between 7-3,000 years BP, mostly evinced by increases in the number of Prepuna perennials as well as the occasional appearance of summer annuals and Tolar taxa. The few middens dated to between 40-22,000 years BP possess very dry assemblages, along with those marking the abrupt onset of aridity after 10,000 years BP. The poor plant assemblages present in middens younger than 3,000 years old also indicate dry climates, possibly the driest over the last 22,000 years. The youngest midden in the record, however, indicates the possibility of a more recent wet phase ~500 years BP.

Middens from further north and at slightly higher elevations in the Cordillera Domeyko are divided into two series, spanning the last 12,000 years BP (west-facing slopes, Fig. 2d) and 13,400 years BP (east-facing slopes, Fig. 2e). West-facing middens at the localities of Tuina (see Fig. 1) and Cerros de Aiquina reflect wetter conditions between 12-9.5 thousand years BP and again between 7.6-6.7 thousand years BP, as inferred from the high percentages of extralocal taxa (generally >40%), steppe grasses and tolar shrubs.

Middens dated to between 9.2-8.4 thousand years BP and those at 5.1 thousand years BP and younger all have much drier plant assemblages.

East-facing middens at the localities of El Hotel and Pampa Vizcachilla, dated to between 13.4-12.9 thousand years BP, are rich in extralocal taxa, steppe grasses and Tolar shrubs (including *Parastrephia quadrangularis*, a high Tolar shrub found today between 3800-4000 m in elevation), all indicating much wetter conditions. A single midden dated to 9.4 thousand years BP displays an array of plant species similar to the modern floras found there today. Total and extralocal taxa increased again in middens dated to between 6.1-3.2 thousand years BP and then decrease in middens dated to between 2,500 and 170 years BP.

Radiocarbon dating of terrestrial macrofossils on terraced palaeowetland and fossil spring deposits along the Río Salado (a tributary of the Río Loa), at Quebrada Puripica and at Tilomonte, indicates times of elevated ground-water tables and increased ground-water recharge (Rech et al., 2002; 2003). Four chronostratigraphic units are recognized: Unit A, dated to older than 44,000 years BP; Unit B, dated to between >15.4-9 thousand years BP; Unit C, dated to between 8 and 3 thousand years BP; and Unit D, which is younger than 1,000 years old. As in the northern Atacama, aggradation of these units culminated in abrupt incision and erosion of the deposits. In some cases (such as with Unit B at the Río Loa and Salado localities) these units may have been completely eroded away before further accumulation resumed.

In summary, the midden and palaeowetland records from the central Atacama are in close agreement, in particular for a major wet phase between >15 to 9,000 years BP. Based on new evidence from our ongoing midden research at Río Salado in the Calama Basin, this wet phase may have begun as early 17.4 thousand years BP, coinciding closely with globally warmer temperatures and the onset of deglaciation at higher latitudes. Further research, however, in the central Atacama will seek to establish the full extent of the mid-Holocene wet phase, dated to approximately 7-3 thousand years BP. Our evidence is at odds with the notion of a "*Silencio Arqueológico*", a conspicuous, temporal gap in the archeological record attributed to greater mid-Holocene aridity (Grosjean et al., 2001; Núñez et al., 2002).

The southern Atacama (24-27°S)

With very little rainfall either from tropical or extratropical sources, this sector is undisputedly the driest portion of the Atacama Desert. Inland penetration of absolute desert may reach 4000 m in altitude along the western slopes of the Cordillera Domeyko, with peaks that here rise to over 5000 m in altitude. Many closed basin *salars* (salt pans and playas) dot the high elevation intermontane basins found between the Domeyko and Andes Cordilleras. Among the most prominent are Salar de Punta Negra, S. Pedernales, and S. Maricunga. The sharp southern boundary of the Atacama is delimited by increased penetration of the westerlies during winter.

Quebrada Chaco is a steep walled canyon occupied by a dry streambed. The stream course begins ~4000 m in the Cordillera Domeyko, starts to form a defined canyon at 3700 m, crosses an active spring just downstream of a 30-m nickpoint and dry waterfall at 3400 m, and eventually shallows into a wide floodplain at 1500 m. Aside from local vegetation around a few springs, there are only a few shrubs and annual herbs below 3500 m which mostly occur along dry washes. Some of the low-elevation plants share a close affinity with those found along the coast in the specialized "*Lomas*" fog communities, endemic relicts that probably formed during the Tertiary (e.g. *Malesherbia* and *Nolana*). These constitute the desert perennials in Figs. 2f-2h. Other species are of Andean affinities (the "Andean" perennials), which become more abundant above 3500 m, although mostly confined to the canyon itself. Starting at 3900 m, extensive low cover grassland appears dominated almost exclusively by a single species of steppe grass, *Stipa frigida*.

We have collected and ^{14}C-dated 42 middens from three different elevations at Quebrada Chaco. The middens were analyzed for both plant macrofossils present (Betancourt et al., 2001; in prep.) and for pollen contained within the midden matrix (excluding fecal pellets) (Maldonado et al., in prep.). The lowermost series (Fig. 2f), collected within absolute desert along a small outcrop of ancient travertines at 2600 m, includes 15 middens that span ages from >52.2 thousand years to 590 years BP. Middens older than 15,000 years BP generally have very rich plant assemblages (especially Andean perennials) and high percentages of extralocals compared to those that date to the last 1,500 years, which are more impoverished. A cluster of high species richness occurs in middens dated to between 23.8-18.1 thousand years BP, although a few older middens with greater richness appear at 38.9 thousand years and >52.2 thousand years BP. Pollen analyses of the midden matrix (excluding fecal pellets) reveals abundant Fabaceae and Brassicaceae pollen between 52 to 33 thousand years BP. Diverse pollen assemblages, which include Brassicaceae, Fabaceae, Asteraceae (Tubiliflora) and Chenopodiaceae pollen, characterize middens dated to between 25 and 15 thousand years BP. Desert taxa pollen (*Cistanthe* and Caryophyllaceae) dominate late Holocene middens younger than 1,500 years BP.

Only six middens spanning the last 8.4 thousand years were collected from intermediate elevations (3100-3200 m) within the canyon. Macrofossil content reveals a stable and arid Holocene (Fig. 2g). Despite a slight increase in pollen diversity after 1,500 thousand years BP, older assemblages are dominated by plants found nearby at a modern spring.

Closer to the lower vegetation limit, at 3450-3500 m, we collected a series of 20 middens spanning the last 40,500 years along several volcanic outcrops (Fig. 2h). The two middens older than 35,000 years have impoverished floras dominated by Andean perennials. Middens dated between 19.6-10.1 thousand years BP, however, exhibit higher numbers of taxa, with middens particularly rich in annuals as well as Andean perennials dated to between 15-10 thousand years BP. Only four middens dated younger than 10,000 years BP, all of which display plant assemblages very similar to modern assemblages. The pollen assemblage from the oldest midden is dominated by Asteraceae (Tubuliflora) and Poaceae. Pollen from middens dated between 20-10 thousand years BP are considerably more diverse, with Poaceae, Asteraceae (Tubuliflora), Chenopodiaceae and *Chaetanthera*-type all present. The genus *Chaetanthera* is found today only in the high Andes close to the upper vegetation limit (~4500 m), and is strong evidence for colder temperatures as well as increased precipitation between 20-15 thousand years BP. Middens between 14-10 thousand years BP show an increase in Brassicaceae and Asteraceae (Tubuliflora) with a concomitant decrease in grass pollen. Younger middens are dominated by Chenopodiaceae and Nolanaceae, implying much more arid conditions throughout the Holocene, save the last 1,000 years, when an increase in Brassicaceae and Fabaceae pollen occurs.

Channel deposits in Quebrada Chaco are 3 to 5-m thick and contain alluvial sediments (silt, sand, gravel) and wetland facies (diatomite, tufa, organic mats). We studied the age, sedimentology, and stratigraphy of channel deposits along a 20 km reach of

Quebrada Chaco and along four of its main tributaries between 2700 m and 3300 m. The sedimentology of channel deposits range from mostly diatomite and organic mats to predominately alluvial sediments with a few beds of organic mats. Thirty AMS ^{14}C ages, mostly on carbonized wood, provide good age control for these deposits. The oldest channel deposits are undated and lie beneath a clear unconformity. Younger channel deposits date between 20.8-10.2 thousand years BP with the majority of deposits dating between 15.4-10.2 thousand years BP. Sequences of diatomite and organic mats are interpreted as marshes/wetlands that were supported by much higher levels of ground water than are currently in the drainage (see Rech et al., 2003, for a recent discussion on wetland deposits in the Atacama).

The majority of wetland deposits in Quebrada Chaco and its tributaries, as well as midden records from upper and lower elevations dating between 15.4-10.2 thousand years BP are in good agreement with late Glacial/early Holocene wet phase indicated in the higher middens (>3450 m) at Quebrada Chaco, and in the central Atacama. Aggradation beginning at ~20.8 thousand years BP, however, agrees with low elevation midden evidence that there was an earlier pluvial period between 23.8-18.1 ka. One source for this earlier pluvial could be the enhancement or northward migration of westerly storm tracks during the Last Glacial Maximum (LGM- ca. 21-17,000 years BP). In the Holocene, absence of wetland deposits along with impoverished midden floras implies widespread aridity, with a slight increase in moisture over the last 1,500 years. This pattern is clearly different from that found further north, and implies that increases in summer precipitation during the middle Holocene were of insufficient magnitude to have reached Quebrada Chaco. Ongoing work in the southern Atacama, at localities directly north and south of Quebrada Chaco, will enable us to place both a maximum northward limit to the westerly excursion during the LGM as well as establishing the southern limit of increased summer moisture during the late glacial and middle Holocene.

Towards a regional synthesis

Figure 3 compares effective moisture interpretations from the diverse array of records of continental climate change now available. Large discrepancies in palaeoclimate interpretation are readily apparent.

- Lake cores from the Altiplano, including Lago Titicaca (Baker et al., 2001b) and Salar de Uyuni (Baker et al., 2001a), seem to indicate a wet LGM (>20,000 years BP) a pattern not seen along the Pacific slope of the Andes except in the Salar de Atacama salt core (Bobst et al., 2001) and in the southern Atacama. There are disagreements between core and shoreline evidence for paleolakes on the Bolivian Altiplano. Twice in the last 110,000 years, overflow from Lake Titicaca inundated and, when lake levels rose above 3700 m, integrated drier basins to the south (Poopó, Coipasa, and Uyuni). The radiocarbon chronology for the oldest shoreline (Paleolake Minchin) above 3700 m is questionable, and in process of being resolved through U-series dating. The younger and higher shoreline above 3700 m (Paleolake Tauca) is also being redated, but previous dates range between 18.9-14 thousand years BP (Sylvestre et al., 1999). On the flanks of Cerro Tunupa in Salar de Uyuni, Tauca shoreline deposits are intercalated with well-dated glacial deposits at ~15 thousand years BP (Clayton and Clapperton, 1997). In the Uyuni and Coipasa Basins there are other minor shorelines (representing smaller lakes that never rose above 3700 m), the most recent one tentatively dated at 10.8-9.5 thousand years BP (Sylvestre et al., 1999).
- A prominent late glacial wet phase (15-10,000 years BP) is seen in all the Atacama records including high Andean lakes such as L. Miscanti (Grosjean et al., 2001) and L. Lejía (Geyh et al., 1999). Despite a clear easterly moisture signal evident in rodent midden assemblages, this wet phase may have had only minor impact at S. Uyuni and S. Atacama.
- A slightly wetter middle Holocene is indicated by midden and palaeo-wetland records throughout the northern and central Atacama but not in the southern Atacama. Probably, the minor increases in easterly rainfall evinced from our records further north may not have been extensive enough to reach Queabrada del Chaco at 25°30’ S. In stark contrast, however, are the high Andean lake records which indicate intense drought during the middle Holocene.

At least some of the discrepancies in the palaeoclimate records may be explained by substantial geographic variation in the sources and mechanisms of precipitation over the central Andes. Summertime precipitation variability in the central Andes is by and large determined by the upper-air zonal wind component aloft, with an easterly (westerly) flow favoring wet (dry) conditions. The influence of these upper-air circulation anomalies on precipitation becomes more dominant when a longer moisture transport is involved and hence is more prominent along the western slope of the Altiplano (Vuille et al., 2000).

For example, Lake Titicaca, which lies at the northeastern margin of the Altiplano, still receives a considerable amount of rainfall under unfavorable atmospheric conditions for the rest of the region (i.e. westerly flow), while this is hardly ever the case for the more remote Salar de Atacama region. On interannual timescales the upper-air circulation over the northern Altiplano (north of ~22ºS) is influenced by SST anomalies (SSTA) in the central equatorial Pacific, with warm (cold) SSTA causing enhanced westerly (easterly) flow, due to changes in meridional baroclinicity between tropical and subtropical latitudes. This mechanism explains the apparent relationship between ENSO and Altiplano rainfall (Garreaud and Aceituno, 2001). General Circulation Model (GCM) simulations, with changed orbital and glacial forcing, indicate that this mechanism observed today may even hold on glacial-interglacial timescales (Garreaud et al., 2003). This might explain why parts of the eastern Altiplano appear wet, and other regions appear dry, such as during the LGM.

Other explanations must be invoked to explain the reverse situation. In particular, how could moisture occur on the Pacific slope while leaving the Altiplano dry? This seems to be the case for the mid-Holocene wet phase of the northern and central Atacama. One possibility is that it could have been caused by an increase in extratropical moisture. The lack of a mid-Holocene wet phase in the southern Atacama seems to preclude this, however. One of the strengths of our transect rests on the fact that downslope migration of plants into absolute desert is almost exclusively controlled by precipitation. At such low precipitation amounts, any moisture increases far surpass any increases/decreases in heatload.

High Andean lake records, however, have also been interpreted exclusively in terms of changes in precipitation. For example, Lake Titicaca experienced a ~4,000 year drought during the mid Holocene from 8-4,000 years BP. Lake levels fell approximately 100 m during this well-dated lowstand. Despite what appears to be a clear drought signal, a recent 20,000 year pollen record from Lake Titicaca indicates an extremely diverse pollen assemblage between 8-3.1 thousand years BP, dominated by Andean cloud forest elements such as Podocarpaceae, Moraceae and other taxa such as *Polylepis* (Paduano et al., 2003). The Andean cloud forest occurs today some 600 m *below* the modern lake level today, implying a direct temperature increase of 2-3° C. The increased temperature added to the additional evapotranspiration caused by what appears to be the most productive ecosystem present in the Titicaca watershed during the entire record, might have been enough to draw down lake levels despite any minor increases in precipitation. The same situation may have applied to another high Andean lake, Laguna Miscanti. Here, pollen concentrations seem to have varied very little during the Holocene, despite sedimentary evidence for strong drop in the lake level between 8-3 ka (Grosjean et al., 2001).

Finally there is one more argument, which provides support for the notion that discrepancies in the palaeorecord might reflect different moisture sources and mechanisms of precipitation. A recent study based on satellite data indicates that precipitation variability in the central Andes shows much less spatial coherence than previously thought, with many years displaying antiphasing of wet/dry conditions between the northern and southern Altiplano (Vuille and Keimig, 2003, in review). South of ~22º S the main moisture source is no longer the Amazon basin but appears to lie to the southeast over northwestern Argentina. Upper-air circulation anomalies with easterly winds favoring wet and westerly winds producing dry conditions still play a crucial role over the southern Altiplano as they do further north. However, the zonal flow appears to respond to extratropical Rossby wave dispersion and modulation of the positioning and intensity of the Bolivian High. In addition, increased precipitation in the southern Altiplano is restricted to periods of higher water vapor content in the moisture source region to the east of the Andes, a mechanism, which is of no relevance over the northern Altiplano region.

One of the major strengths of the Atacama record is the ability to discriminate between temperature and precipitation effects. Our records suggest that the upper-air circulation, responding to changes in tropical Pacific SST-gradients and related changes in the moisture source region to the east are more important than local insolation to explain the late Quaternary changes in the Atacama Desert. Increases in westerly moisture, clearly seen in the southern portion of the Atacama, may not have been extensive enough to have impacted areas further north. In a likewise manner, minor increases in precipitation that occurred during the mid-Holocene, were of insufficient magnitude to impact areas south of 25°S. Ongoing research in the southern Atacama will help clarify the northward (southward) extent of the westerlies (easterlies) during the LGM and late glacial period.

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Legends to Figures

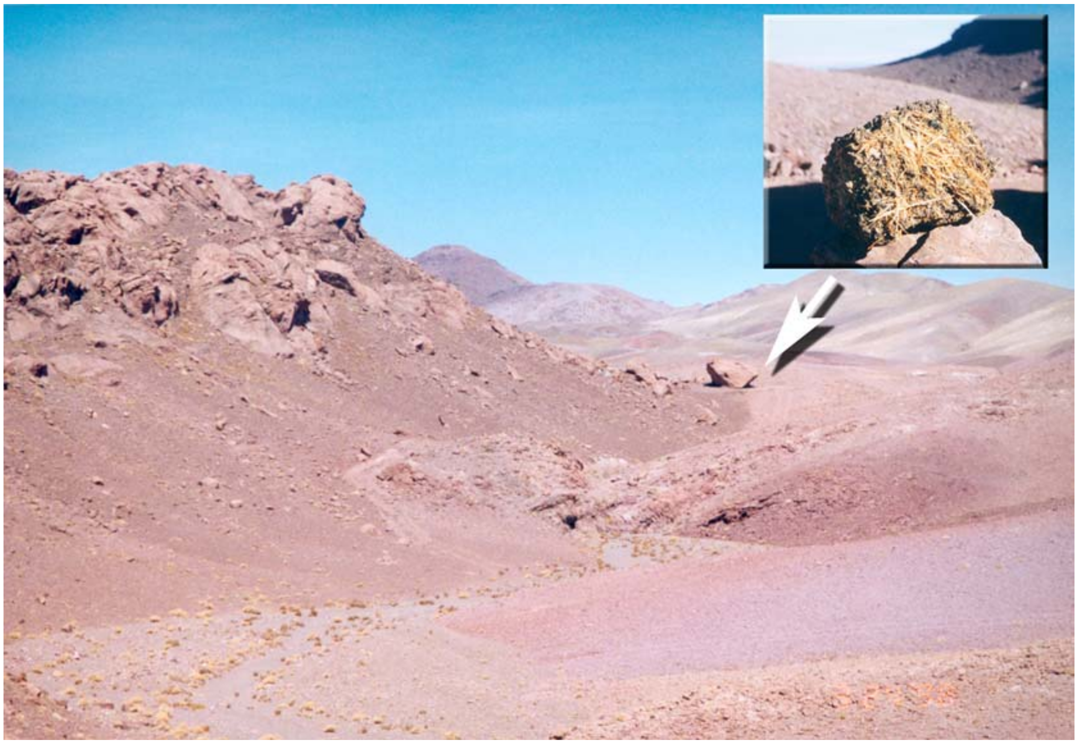
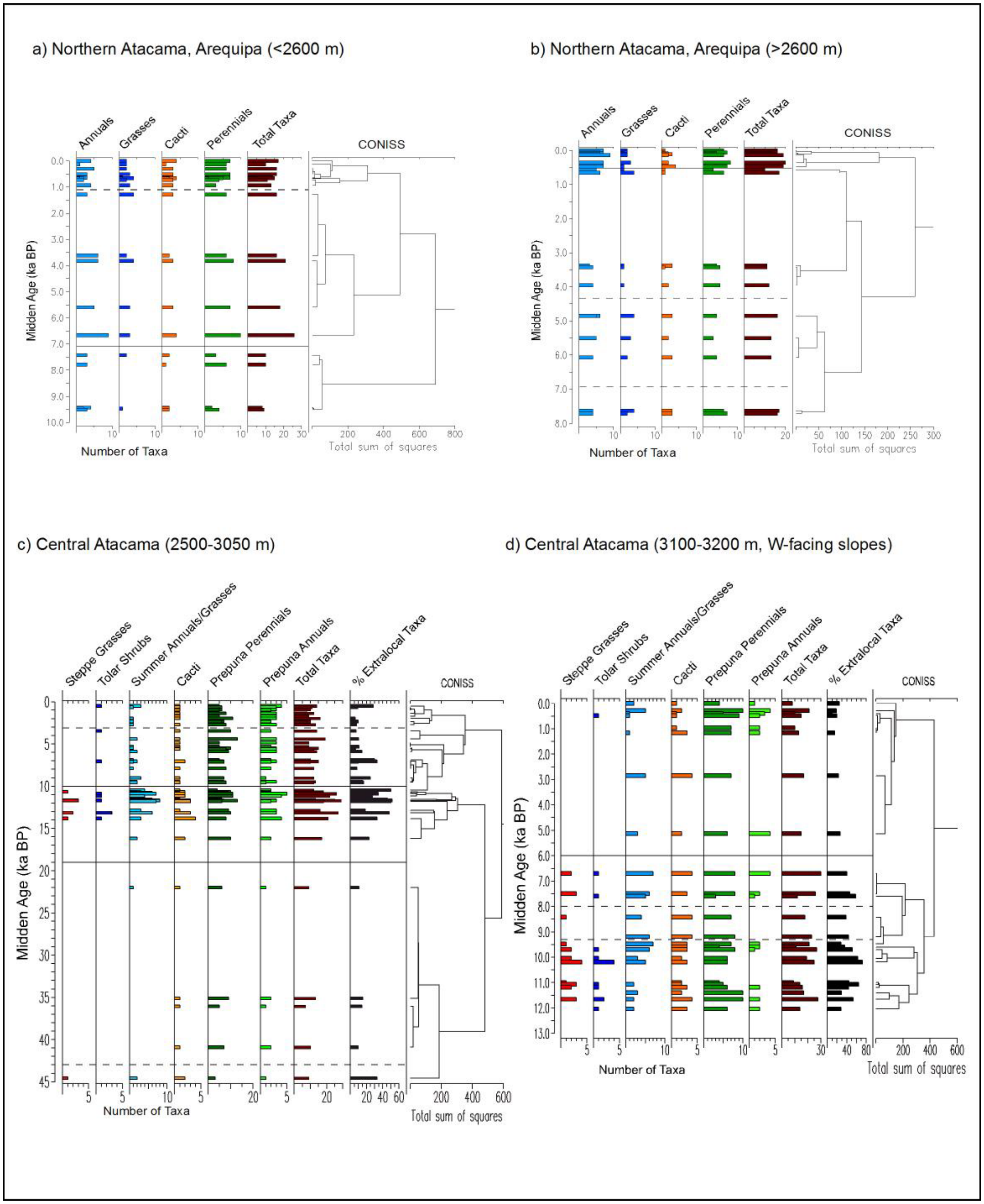


Figure 1.

An aspect of the Tuina midden locality (elevation: 3190 m) located along the eastern margin of the Calama Basin. Scant *Prepuna* vegetation present on slopes and in dry wash is dominated by salt bush (*Atriplex imbricata*) and cushion cacti (*Opuntia* spp.). The arrow points to Tuina rock shelter, which not only harbors the oldest archaeological site in the region (see Nuñez et al., 2002) but also several of the middens depicted in Figure 2d. **Inset**: A vizcacha midden dated to 11,650 years BP found within the rock shelter. Most of the abundant grasses present are found only in the High Andean Steppe today.



a) Northern Atacama, Arequipa (<2600 m)
Annuals
Grasses
Cacti
Perennials
Total Taxa
CONISS
Midden Age (ka BP)
Number of Taxa
Total sum of squares
b) Northern Atacama, Arequipa (>2600 m)
c) Central Atacama (2500-3050 m)
Steppe Grasses
Tolar Shrubs
Summer Annuals/Grasses
Prepuna Perennials
Prepuna Annuals
% Extralocal Taxa
d) Central Atacama (3100-3200 m, W-facing slopes)

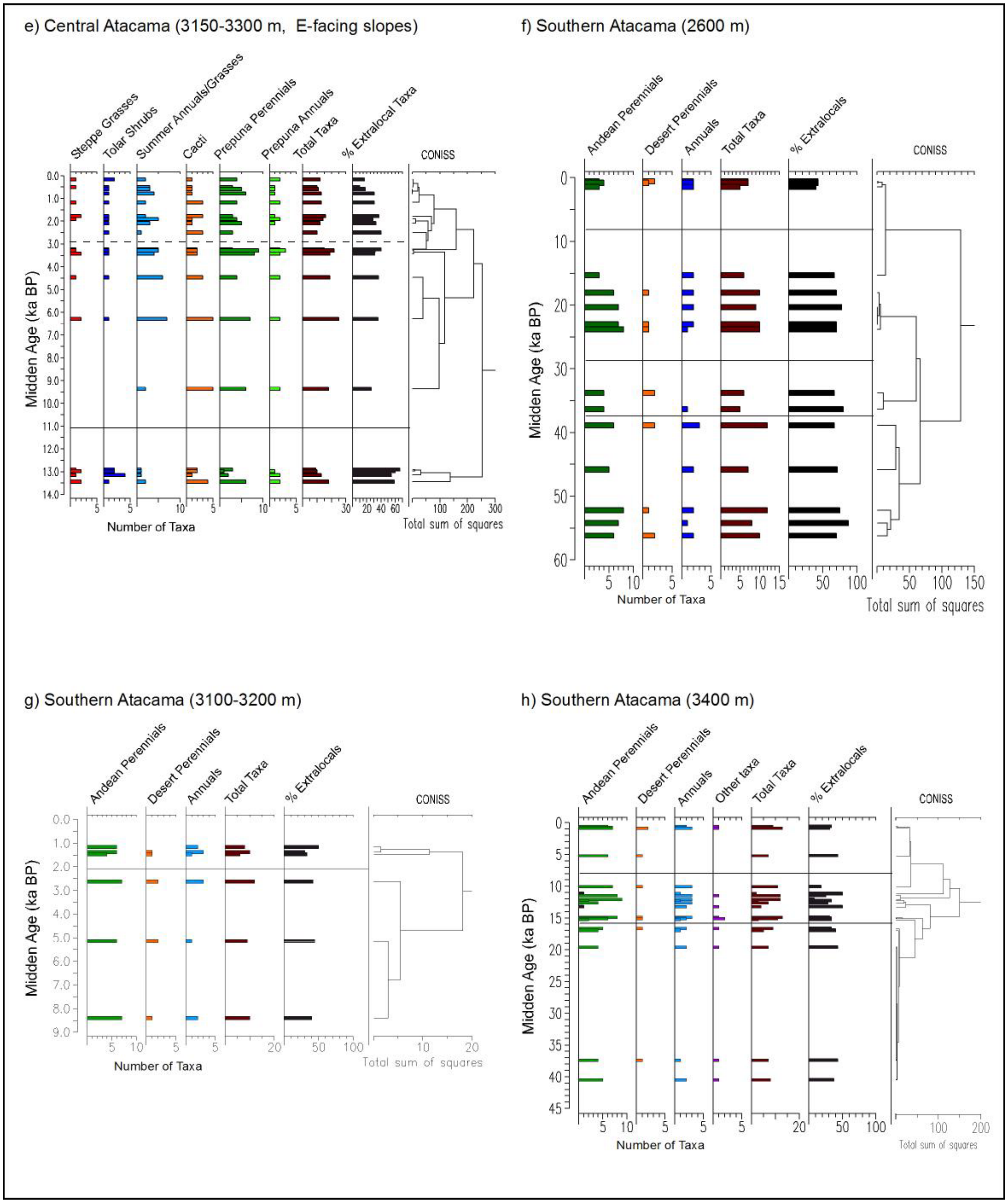


Figure 2.

Rodent midden records from the Atacama Desert, summarized by plant life-form and phytogeographic affinity. Major vegetation breaks, in part established by a CONISS (Constrained Sum of Squares) cluster analysis, are shown as solid black lines. Minor breaks are shown as dotted lines. Note changes in scale.

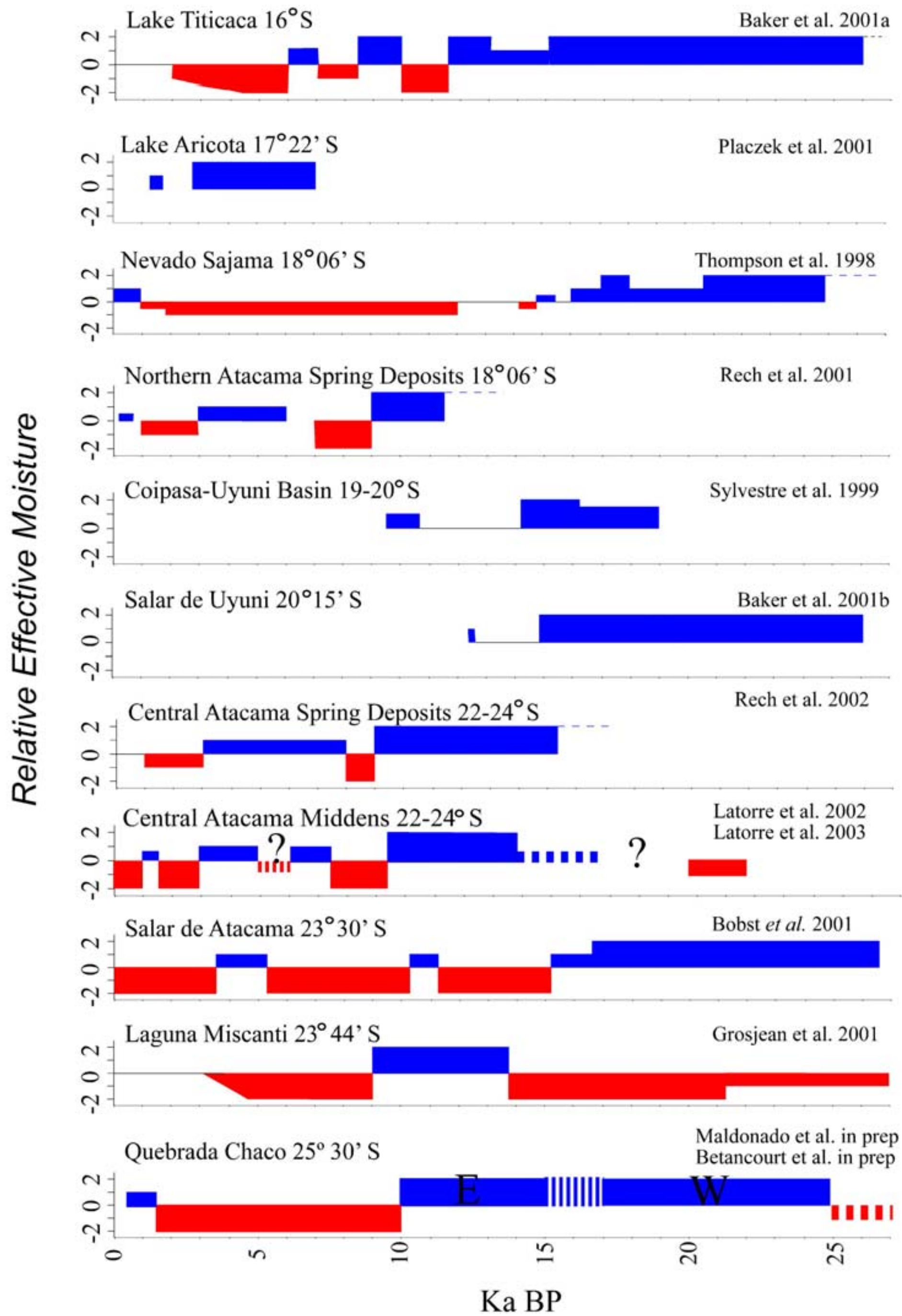


Figure 3.

A regional comparison of paleoclimate records along a N-S transect across the central Andes and Atacama Desert. Dry phases are indicated in red whereas blue denotes wet phases. For the southern Atacama record, the E and W indicate easterly and westerly sources of moisture respectively.

Author Bios

Claudio Latorre, received his PhD in 2002 in Ecology and Evolutionary Biology from the Universidad de Chile, Santiago, Chile, and worked on developing a midden record from the central Atacama, the first for Chile. He is currently a postdoc with the Department of Ecological Sciences at the Universidad de Chile. He is currently working on the modern climate/vegetation relationship throughout northern Chile as well as expanding and refining the Atacama midden record.

Julio Betancourt is a paleoecologist with the U.S. Geological Survey and an adjunct professor at the University of Arizona in Tucson, Arizona, USA. He is based at the Desert Laboratory, a research institution with a 100-yr legacy in environmental studies (http://wwwpaztcn.wr.usgs.gov/). Focusing on the Western Hemisphere, he has spent the last 25 years using various techniques (rodent middens, tree rings, isotopes and ancient DNA) to study the influence of climate variability on physical and biological systems at interannual to millennial time scales.

Jason Rech is an Assistant Professor at the Department of Geology at Miami University (Ohio), USA. His major research interests are in surface processes and climate change in arid lands. His work in the Atacama includes using wetland and spring deposits to infer changes in ground-water recharge, stable isotope geochemistry of pedogenic salts to determine source and transport paths, and the use of pedogenic salts to understand the climatic evolution of the Atacama Desert over the Miocene.

Jay Quade is a geochemist with the Department of Geosciences at the University of Arizona and based at the Desert Laboratory, Tucson, Arizona, USA. His interests are in using geochemical tracers such as stable isotopes in paleosols, speleothems, and lacustrine carbonates to reconstruct Tertiary paleoenvironments. Current areas of study include the Atacama Desert of South America, the Himalaya, Ethiopia, and the desert southwestern U.S.

Camille Holmgren is a paleoecologist and doctoral candidate at the University of Arizona. For her master's thesis, she developed the first fossil rodent midden study in Peru and is now developing a vegetation history of the U.S.A.-Mexico Borderlands for her doctoral dissertation.

Christa Placzek is a geologist/geochemist and doctoral candidate at the University of Arizona. She reconstructed Holocene lake levels on the west flank of the Peruvian Andes for her master's thesis. She is currently mapping and using U-series and radiocarbon analyses to date shoreline deposits of the large paleolakes that waxed and waned over the last 110,000 years on the Bolivian Altiplano.

Antonio Maldonado is a palynologist finishing his PhD at the Universidad de Chile. He has worked extensively on the history of relict swamp forests in the semiarid region of Chile north of Santiago as well as developing a pollen record from rodent middens in the southern Atacama. He has recently been hired by the Centro de Estudios Avanzados de Zonas Áridas (CEAZA) located at La Serena, Chile.

Mathias Vuille received his Ph.D. in Physical Geography from the University of Bern, Switzerland in 1995, studying spatiotemporal variability of winter snowfall in the northern Chilean Andes. His postdoctoral work at the University of Massachusetts focused on interannual climate variability in the tropical Andes. He currently holds a position as a Research Assistant Professor at this University. His research interests are in climate variability of the tropics, and in particular the Andes of South America, from intraseasonal to glacial-interglacial timescales.

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