A review of multiproxy temperature and precipitation reconstructions for South America during the Holocene

Master's Thesis

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Abstract

This master thesis gives an overview on existing studies and data sets to diagnose Holocene climate in South America. Available data are categorized referred to the mean Holocene value and 250-years-classes are built. Due to changing data quality the scattering range decreased toward the present. The wet Coipasa event in the early Holocene is detected in most data sets. A wet early Holocene is suggested in southern South America, in the Andes and in the Caribbean. The arid mid-Holocene was confirmed in the northern and central Andes and in the Caribbean. A dry late Holocene in the central and northern Andes as well as in the Caribbean region is believed to have occurred. In contrast, other studies suggested wet late Holocene conditions.

The early Holocene started with low temperatures in the Andes and in the Caribbean, what could imply an influence of the cold Younger Dryas. In the Andes, the mid-Holocene temperatures fluctuate around the Holocene's average values. The temperature dropped in the late Holocene, which can be related to the Little Ice Age. The current temperature increase cannot be seen due to the coarse data resolution (250-years-classes).

This work confirms the general southward shift of the Inter-Tropical Convergence Zone (ITCZ) during the Holocene. The dry mid Holocene in northern South America could have been caused by a reduced annual movement of the ITCZ toward north and south, or it could have been caused by a shift of the ITCZ.

Further influence of the position of the subtropical high pressure cell and the circumpolar low pressure belt was taken into account. If the subtropical high pressure cell is located near the equator, the precipitation increases in central Chile and eastern Patagonia. In contrast, increased precipitation over northern Chile and southwest Patagonia results in a displacement of the subtropical high pressure cell to higher latitudes. A circumpolar low pressure belt close to Australia is responsible for higher than normal precipitation over northern Argentina only. Its shift to South America causes increased precipitation in central Chile, Argentina and southeast Patagonia. In the early and mid Holocene the subtropical high pressure cell was close to the equator and the circumpolar low pressure system shifted toward Australia. For a short time around 8,500 yBP the circumpolar low pressure belt moved toward South America. The subtropical high pressure cell moved to higher latitudes in the late Holocene. Between 5,000 yBP - 3,000 yBP the circumpolar low pressure cell was closer to South America and then moved back again to Australia.

The available studies are not sufficient to make final conclusions about the prevalent climate conditions and the large scale climatic and synoptic patterns during the Holocene. Especially temperature data is scarce. Some climatic patterns are just documented by one proxy. Further data sets would be required to verify available studies and to gain new insight in other regions.

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Abbreviations

AAO	Antarctic Oscillation
AO	Arctic Annular Mode
ENSO	El Niño/Southern Oscillation
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
LIA	Little Ice Age
MJO	Madden-Julian Oscillation
NAO	North Atlantic Oscillation
PDO	Pacific Decadal Oscillation
SA	South America
SACZ	South Atlantic Convergence Zone
SAMS	South American Monsoon System
SST	Sea Surface Temperature
Ti	Titanium
yBP	Years Before Present (before 1950)
YD	Younger Dryas

1. Introduction

1.1 Motivation

Climate change heavily impacts economical and ecological systems and consequently influences everyone's daily live. A lot of effort and also financial resources are dedicated to research the impact of climate change and future climate conditions. To achieve success in climate research, accurate climate information from the past is required. First, instrumental measurements became available earliest 150 years ago, depending on the region. First area wide climate information was made possible by satellite measurements. In 1960 the first satellite Trios 1 was commissioned (Häckel 2005). Before the time of instrumental measurements, climate reconstruction is needed. Palaeoclimate research deals with palaeoarchives, where climate information is stored in different variables (proxies). Multiproxy analysis gives the opportunity for richer and more complete views of climate situations of each time period (IPCC 2007 d). It is assumed that tropical proxy records might be more representative of global mean annual temperature values than records of higher latitude (Bradley 1996). Additionally, a full overview of the past climate helps to understand the mechanisms of climate systems and makes it possible to verify and improve today's climate models (IPCC 2007 d).

Up to date, different palaeodata has been collected in South America (SA). Aim of this thesis is to give an overview about existing studies of temperature and precipitation during Holocene in SA. Additionally, it will become clear where next data sets will be needed.

1.2 Present climate in South America

SA's climates are tropical, subtropical and extratropical. The climate is influenced on one side by the global pattern and on the other side by regional characteristics like topography.

The Brazilian plateau blocks the low-level circulation over subtropical SA. The Amazon rain forest is a result of this blocking effect. The north-south adjusted Andes Cordillera also acts as a wall for moisture origin from the Amazon. The result is a dry climate on the Andes west side and wet climate on its east side at low latitude and an opposite hydrology in the middle latitudes (Figure 1).

During austral summer a continental low pressure develops over the Chaco region (Figure 1). This helps the east wind turning over the Amazon basin to south. The air is channeled between the east side of the Andes and west side of the Brazilian Plateau. A low-level jet structure dominates there.

Also in the austral summer, the Bolivian High affects the SA climate. Over the Amazon Basin, convective air ascends, at higher altitude, around 200 hPa, the Bolivian High develops.

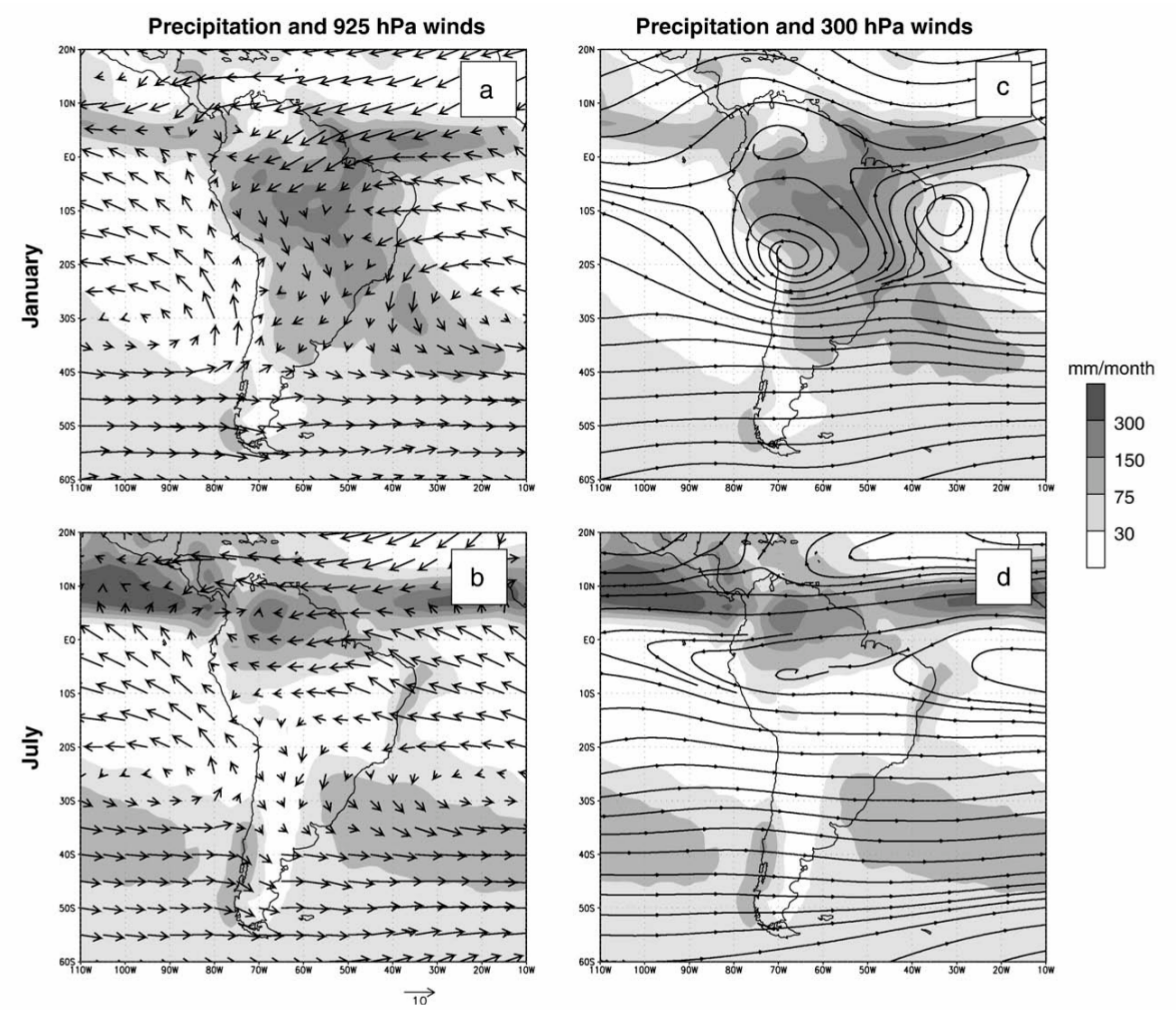

Figure 1: Left panels: long-term mean precipitation (shaded – scale at right) and 925 hPa wind vectors (arrows – scale at bottom) for (a) January and (b) July. Right panels: long-term mean precipitation (shaded – scale at right) and streamlines at 300 hPa (streamlines) for (c) January and (d) July (Garreaud 2009).

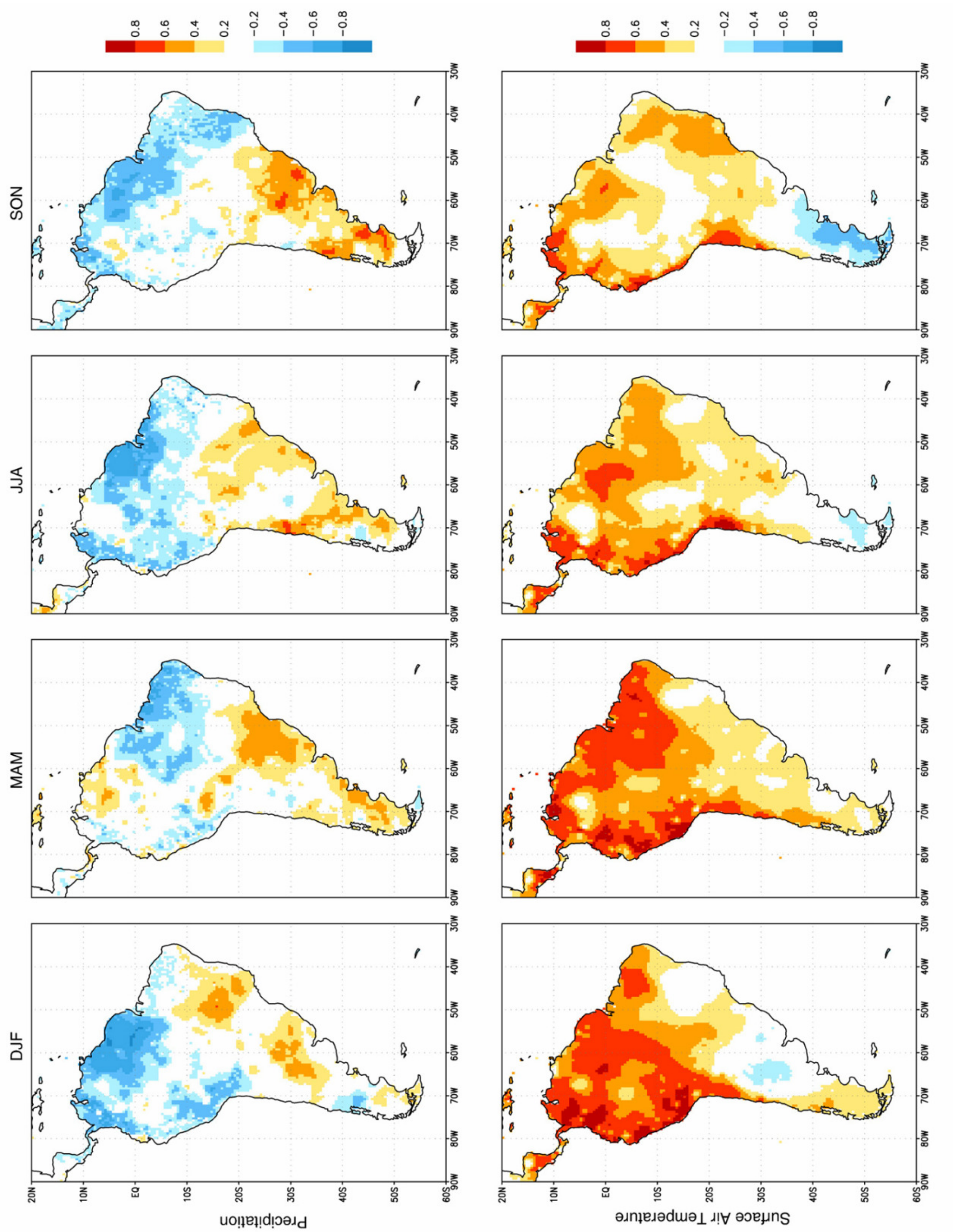

Figure 2: Seasonal precipitation and surface air temperature in SA (Garreaud 2009).

The Intertropical Convergence Zone (ITCZ) is responsible for precipitation around the equator (Figure 1) and is a band of minimum pressure. Trade winds compensate this low pressure. In this way, the ITCZ dominates low level convergence resulting in significant convection and convective precipitation. The ITCZ is a result of ocean- atmosphere feedback and is additionally influenced by the coastline. In the East Pacific, these factors cause a shift by 5° to the north of the ITCZ, in year-average. This phenomenon is called northerly ITCZ bias (Garreaud et al 2009).

The seasonal precipitation and surface air temperature is plotted in figure 2. In Brazil, Venezuela, Guyana and eastern half of Columbia, tropical climate dominates. A northwest – southeast oriented convergence zone is found across southeastern Brazil and the western South Atlantic. This area with clouds and precipitation, which is strongest in the summer, is called South Atlantic Convergence Zone (SACZ). This seasonal difference was described by scientists in the last decade and is today known as South American Monsoon System (SAMS) (Garreaud 2009 and AMS 2010).

Desert climate can be found on one hand west of the Andes in countries such as Columbia, Ecuador, Peru and the northern part of Chile, on the other hand desert climate also prevails in South Argentina. A so called Arid Diagonal appears from northwest SA to southeast SA.
The climate type of South Chile, North Argentina as well as Paraguay, Uruguay and the southern end of Brazil is warm temperate (Garreaud 2009 and Kottek et al. 2006).

The SA climate is part of the global climate system. Climate parameters are influenced by regional factors as described above, but also by teleconnection of modes and global climate forcings.

An important feature for SA climate is the so called El Niño/Southern Oscillation (ENSO). This phenomenon occurs in the Pacific between Indonesia/Australia and Peru/Ecuador. A ‘normal’ pattern in the Pacific Ocean is plotted in figure 3b. The Sea Surface Temperature (SST) in the West Pacific is warm. In contrast, cold deep water reaches the ocean surface at the coast of the East Pacific. The East Pacific SST can be up to eight degrees lower than the West Pacific SST. The ocean current is driven by the easterly winds. The atmospheric part of this system is called Walker Circulation. At sea surface the air is moved to west by trade winds. The West Pacific is warmed up and moist air evaporates and ascends. At high altitudes, the trade winds are compensated in eastward direction. At the coast sides of Peru and Ecuador the dry air descends.

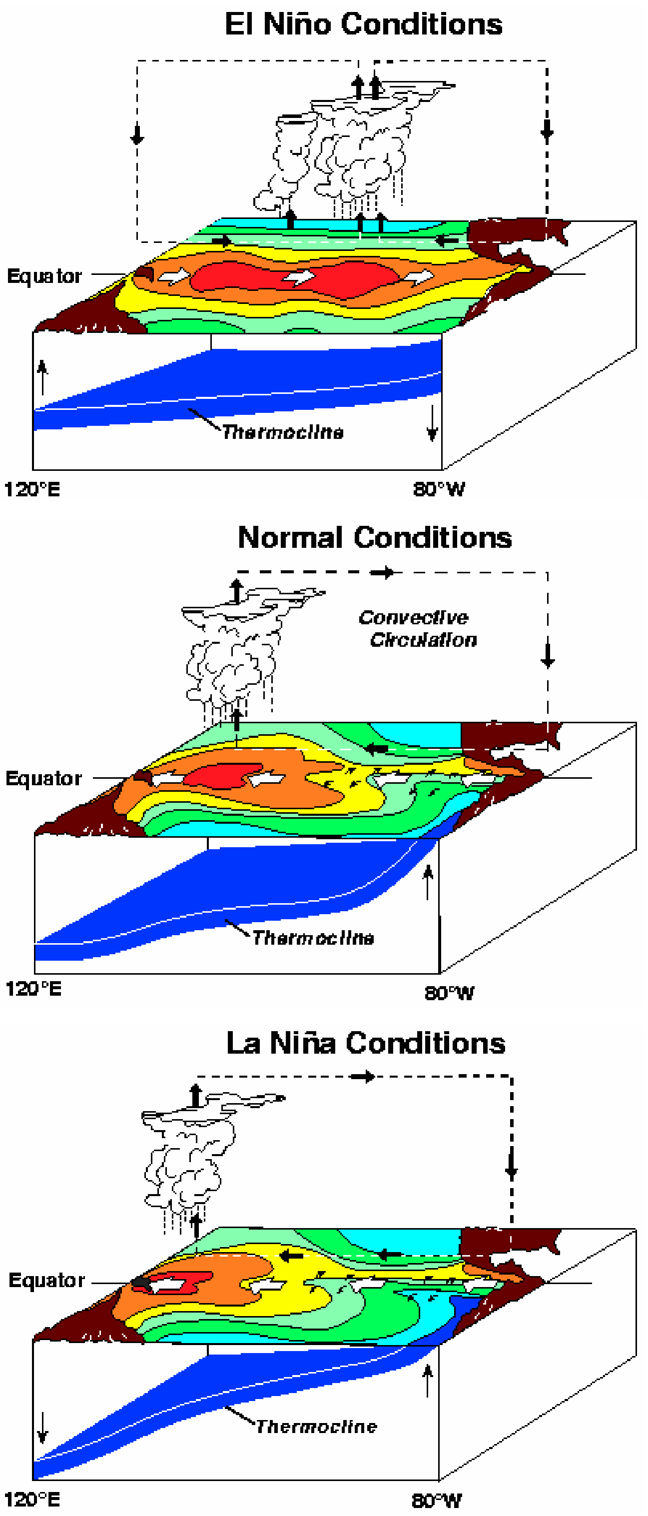

Figure 3: Condition for a) El Niño, b) normal situation and c) La Niña in Pacific Ocean (NOAA 2010)

At El Niño condition (Figure 3a) the trade winds change their direction to west. Warmed sea surface water reaches the West Coast of SA resulting in a descending thermocline. Moist air ascends in the middle Pacific causing a high pressure system. The moist air is transported at higher altitudes to the coastal region of SA, where the air is blocked by the Andes which is responsible for severe rain falls often associated with floods, while in Indonesia and Australia droughts dominate. This system is comprised by an atmospheric (Southern Oscillation) and an ocean component (El Niño).

The La Niña pattern, the opposite of the El Niño pattern is an enforced normal pattern. (Figure 3c) however its convection is moved further west. This results in increased precipitation in Indonesia and Australia. The upwelling of cold deep water is stronger and the band of cold water at the coasts of Peru and Ecuador is enlarged (IPCC 2001 and NOAA 2010).

Beside ENSO, other modes such as Antarctic Oscillation (AAO), Arctic Annular Mode (AO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) and Madden-Julian Oscillation (MJO) play a role. To what respect the SA climate is influenced by these modes is still subject to research. This is the reason why these climate situations are not discussed in more detail here.

1.3 Forcing and natural variability

Global forcing is an important factor in influencing the global climate, in particular also the climate of SA. The driving factors can be distinguished in natural and anthropogenic forcing. There are three predominant natural forcings such as orbital forcing, solar forcing and volcanic forcing.

Orbital forcing is caused by the earth's orbital elements (eccentricity, obliquity and axial precession) which strongly influence the amount of solar radiation arriving the earth's surface (Figure 4). These elements act in different time scales. Changes in the earth's orbital eccentricity produce periodicities around 400,000 and 100,000 years, obliquity has a periodicity around 41,000 years and earth's axial precession periodicity is 23,000 years. Figure 5 shows the calculated deviations of the insolation form the long-term mean values as a function of latitude for the past 6,000 years. Besides melt water, these elements are responsible for the changing climate between glacials and interglacials (e.g., Holocene).

Solar forcing is caused by the changing radiation of the sun. The total solar irradiation varies about 1% (0.24 W/m^2) over an eleven years cycle (the Schwabe cycle). This is a result of

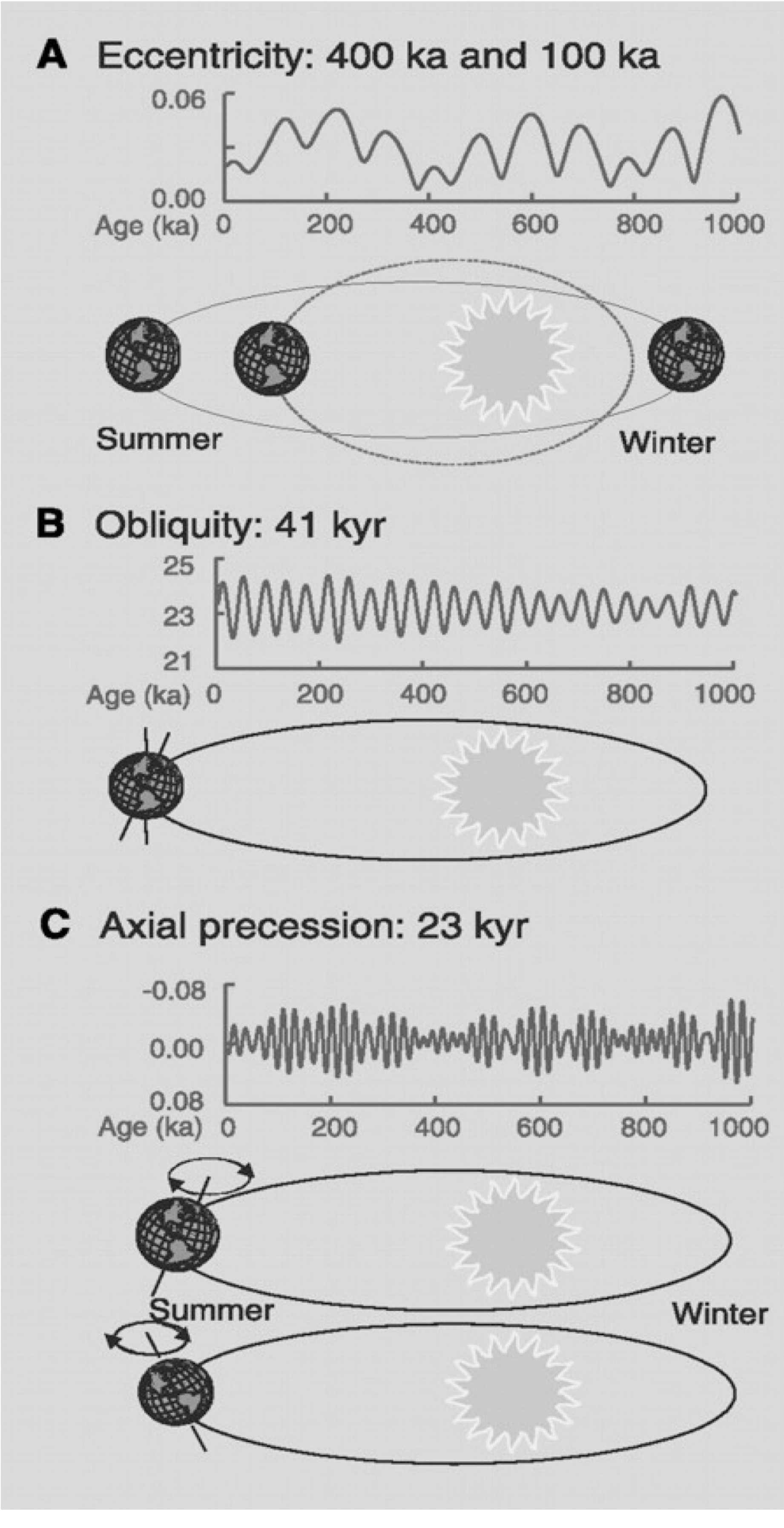

Figure 4: Earth orbital elements. A: eccentricity of the Earth, B: axial tilt (obliquity) and C: precission ('wobbling') of the Earth's axis (Zachos et al. 2001).

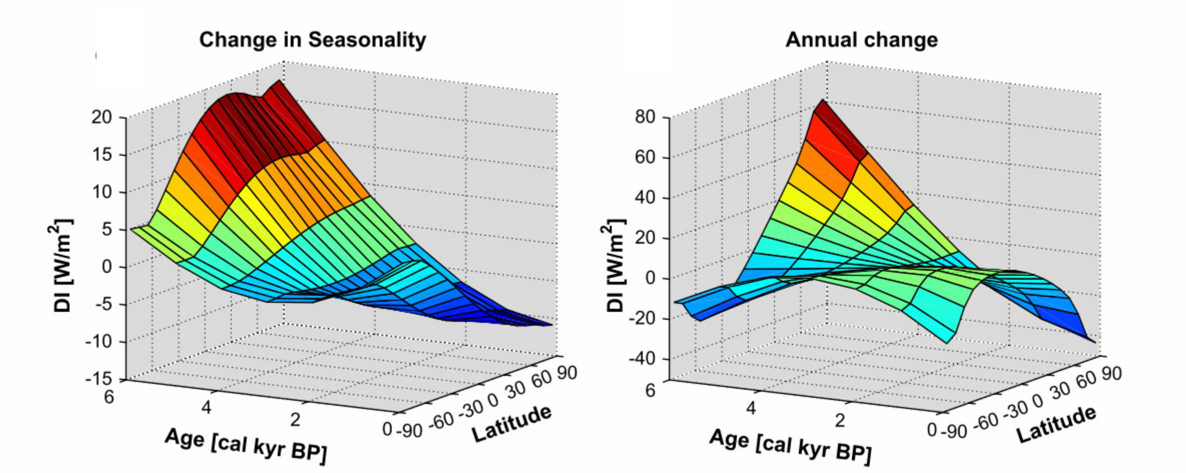

Figure 5: Calculated deviations of the insolation from the long-term mean values (W/m2) as a function of latitude fort he past 6000 years. Left: seasonality (difference between June and December), right: annual mean (Wanner et al. 2008).

darkening by sunspots and brightening by facalae. Recent studies suggest, that these variations in solar activity can affect climate on multi-decadal to centennial timescales.

Volcanic forcing is caused by volcanic eruptions catapulting gases and aerosols into the atmosphere. Volcanic forcing is strongly affecting the regional climate, especially when the aerosols reach the stratosphere. The aerosols absorb solar radiation and cause a cooling of the earth's surface which can last up to few years (Wanner et al. 2008).

Volcanic forcing and solar forcing are the dominant factors for changes during the Holocene.

The recent temperature rise was caused anthropogenic. Anthropogenic forcing is related to the greenhouse effect, aerosols, ozone depletion and land use change. The temperature has been increasing for the past hundreds of years. For studying the Holocene climate, this effect is quite small. Besides deforesting in earlier centuries, the anthropogenic effect has been most permanently increasing steadily in the past two hundred years (IPCC 2007 c, IPCC 2007 d). In this thesis, the data is averaged over 250 year intervals almost eliminating the anthropogenic effect.

1.4 Holocene

Earth's history is divided in different epochs. Holocene is the last part of the final epoch, the so called Quaternary epoch. The Holocene is the intersection between the last Ice Age and today's climate state. The beginning of the Holocene is varying between 10,000 yBP and

12,000 yBP, depending on literature (Leser 2005 and IPCC 2007 b). Here, the Holocene is taken as the last 12,000 yBP, as defined in 1983 by Markgraf. By definition, the Holocene started after the cooling of the Younger Dryas.

The radiative forcing was low in the last Ice Age 20,000 years before 2005. Since then, the temperature is increasing and is highest at the present. This temperature rising indicates the change from the last Ice Age to the Holocene. During Holocene, the values are plateauing. The current increase of temperature is also clearly seen.

If only the last 10,000 years are analyzed (Figure 6), some fluctuations are seen. This study analyses the time series of temperature and precipitation in SA during Holocene (last 12,000 yBP).

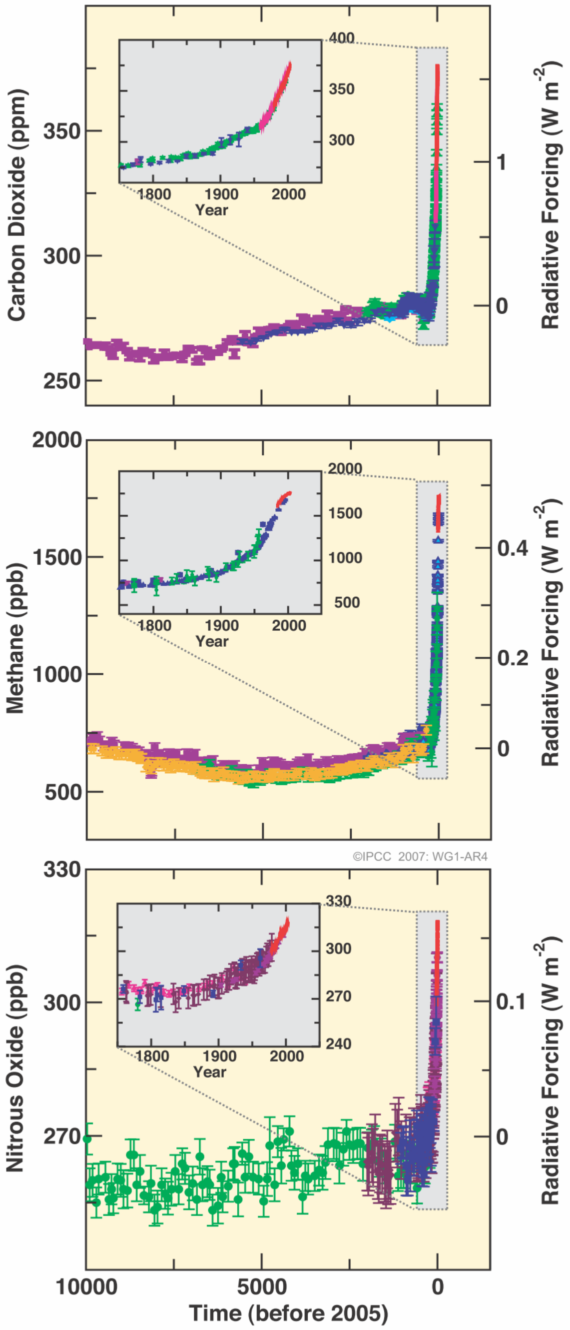

Figure 6: «Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (insert panels). Measurements are shown form ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels.» (IPCC 2007 e)

2. Data and Methods

2.1 Data sets

2.1.1 Proxies and selection criteria

To gain climate information for the Holocene, it is necessary to use proxies. «A proxy climate indicator is a local record that is interpreted, using physical and biophysical principles, to represent some combinations of climate-related variations back in time. Climate-related data derived in this way are referred to as proxy data. Examples of proxies include pollen analysis, tree ring records, characteristics of corals and various data derived from ice cores» (IPCC 2007 a).

Archives can be divided in natural archives and documentary archives. Documentary proxy types are for example flowering and harvest time, profits of wine, water levels in rivers and lakes, glaciation of rivers and lakes, snowfall, flood and low water. Examples of natural archives are tree-rings, fossils of plants and animals, pollen and spores, corals, ice cores, terrestrial sediments and lake sediments (Pfister 1999). Documentary proxies are not used in this thesis. Different natural proxies were tested for their usability. The following criteria are applied:

1. Proxies have to be an indicator for temperature or precipitation.

2. As explained in chapter 2.1, values of 250 years were averaged. The mean of all 250-years-average-classes are used to calculate the category value. It is important, that the average value is as accurate as possible. Therefore, more than 90 % of all classes of the last 12,000 years must be present.

3. The climate related interpretation of the proxy must be comprehensible.

Although pollen data is covering the whole Holocene, SA pollen data is not usable for this study. The temporal resolution of the available data is extremely irregular and the pollen classes are incomplete.

Coral and ice core records often are discontinuous, except those of the last 2,000 years (Rodbell et al. 1999). Nevertheless, some data sets of ice cores with high resolution were found and used for this study. Various gases are conserved in air bubbles. Parameters such as dust, concentration of acids and tracer gases, oxygen isotopes ($\delta^{18}O$), hydrogen isotopes as deuterium (δD) can be extracted (Thomas et. al. 2007).

Sea and lake sediments store indirect climate information in high temporal resolution. Climate related processes, such as floods or mudslides, correlate to climate parameters. To correspond the data sets to a time value an age model is used. The need for a precise age model is the challenge of this method.

Due to indirect climate signals of most proxies, the interpretation brings some problem. Proxies can have more than one origin (for example anions or metal concentration) which makes the interpretation difficult (Thompson et al. 1998, Haug et al. 2001, Moreno et al. 2007). Some proxies such as NO_3^- are poorly understood (Thompson et al. 1995). Furthermore, there are some uncertainties in proxy dating, for example due to the reservoir effect which only can be estimated (Fritz et al. 2004, Geyh et al. 1999, Rein 2007). Some proxies are indicators for extreme events. An increased number of floods, for example, does not mean a general wet time period. Finally, the interpretation of proxies always contains some uncertainties. In this study, the proxy interpretation of the original paper is adopted.

Due to the above defined criteria, many data sets could not be used. A list of not used data sets is found in the appendix. Important data sets are discussed in chapter four.

2.1.2 Data sets

Lake sediments data sets were used at different locations. Sediments are very useful for climate reconstructions. Sediments store biological remains and chemical components, which can be analyzed at a later point in time. This type of archive has the opportunity to gain an extended image of that time period’s dominant climate, if different components of sediments are combined (Batterbee 1991).

Selzer et al. (2000) determined the difference between $\delta^{18}O_{calcite}$ and $\delta^{18}O_{ice}$, in the Huascarán region. Their samples of $\delta^{18}O_{calcite}$ come from Lake Junin which is located at 4,000 meters above sea level between Cordillera Oriental and Cordillera Occidental of the Andes. Nevado

Huascarán, where the ice record hails from, is located 225 km northwest of Lake Junin. The difference between $\delta^{18}O_{calcite}$ and $\delta^{18}O_{ice}$ is an indicator of effective moisture.

In contrast, Moy et al. (2002) detected color intensity of lake sediments. In this thesis, red color intensity of Laguna Pallcacocha at Huascarán at southern Ecuadorian Andes is used. Laguna Pallcacocha is a high altitude lake of 4,200 meters above sea level. In this lake, eroded landscape material and debris-flow material is accumulated. If there is more precipitation, the sediment load is increasing.

At the alpine lake Laguna Pallcacocha at 4,060 meters above sea level, Rodbell et al. (1999) detected grey scale intensity as a proxy for storm induced debris flows. Laguna Pallcacocha is located 75 kilometers east of Pacific Ocean in Ecuador.

The Lake Titicaca, located in the Altiplano in the northern Andes, is the highest (3,810 meters above sea level) large lake in the world. The lake can be divided in two sub-basins, namely the Chucuito sub-basin and the Huiñaymarca sub-basin which are separated by a sill called Strait of Tiquina. There, Tapia et al. (2003) gained records of diatom stratigraphies.

Further south at Bolivian Altiplano region, Fritz et al. (2004) determined salt units by gamma radiation as a proxy for precipitation. Salar de Uyuni, where the samples were found, is the world's largest salt flat, located at a high-elevation plateau at 3,653 meters above sea level. During dry periods, more salt is available in sediments.

Lake Valencia's water level is at 402 meters above sea level. Lake Valencia in Venezuela is close to the sea side of the Caribbean Sea and is the largest freshwater body in northern SA. This lake changed back and forth between closed and open hydrology. Today, the system is closed. Crutis et al. (1999) used sediment geochemistry and $\delta^{18}O$ records from ostracod and gastropod shells. In this study $CaCO_3$ is used as an indicator for hydrological conditions.

The method of climate reconstruction by sea sediments is closely linked to lake sediments. Rein et al. (2007) sampled at a small basin of the edge of a shelf, which is 80 km off Lima (Peru). They analyzed lithic concentrations in shelf sediments as an indicator for flood events.

Haug et al. (2001) measured titanium (Ti) concentrations at Cariaco Basin. The Cariaco Basin is located at the northern shelf of Venezuela. This Basin is highly sensitive to climate changes (Peterson et al. 2000). Titanium is a proxy for the hydrological cycle (Haug et al. 2001). Peterson et al. (2000) measured color reflectance of sediments originating from the same basin and Lin et al. (1997) analyzed stable isotopes of foraminiferal $\delta^{18}O$. All these proxies are taken as an indicator for precipitation.

Lea et al (2003) took also samples of the Cariaco Basin, but they analyzed the Mg/Ca relation as a sign for changes in SST, which is influenced by the air temperature.

There are two more locations of temperature reconstruction. Both are placed in the Andes. One is at Huascarán (Thompson et al. 1995), the other at the summit of the Sajama mountain in Bolivia, close to Lake Titicaca (Thompson et al. 1998). Holocene temperatures are stored in ice. In both locations differences in oxygen isotope ratios $\delta^{18}O$, insoluble particles (dust) and major anion concentrations (Cl-, NO3-, SO42-) were found (Thompson et al. 1995, Thompson et al. 1998).

In this work, storm events such as debris flows are also taken as an indicator for precipitation. This study recognizes the problem, that the number of debris flow does not mandatorily imply a wet and dry climate.

2.2 Methods

Data sets are analyzed by the statistic program "R". First, data was plotted as shown in figure 8. Above the plot, the name of the distributor of the data set is given. The subtitle on the bottom indicates the used proxy. The measured value is plotted against the time scale. Only values of the last 12,000 years, known as the Holocene epoch, are taken into account.
Next, all values are adjusted to year before present (yBP). Then, all values of every 250 years are averaged, for two reasons: First, building 250-year-classes helps to eliminate local influences and short time scale events. Second, the temporal resolution of the used data sets varies. With this procedure, it is easier and more precise to compare classes. Figure 9 shows a example of the classified data set of titanium concentration in the Cariaco Basin. Titanium concentration is an indicator for hydrological cycles. The red line represents the mean value of all classified values of the last 12,000 years.

In a next step, the data set is categorized to allow the comparison of different data sets. The average value, in figure 9 marked with the red line, is set to zero. The highest value is assigned to plus three, the lowest value to minus three. The other values are proportionally stretched. Figure 10 shows the resulting plot of categorized and classified values. The categories in figure 10 are marked with colors. Higher values than two are marked dark green and indicate much wetter conditions respective to the average of the last 12,000 years. Light green stands for values between one and two and represents slightly wetter condition than the Holocene's average, while light brown with values between minus one and minus two, marks time periods with slightly dryer conditions. Extreme dry classes with values lower than minus two are colored dark brown. Values between plus one and minus one are taken for a normal situation and are marked white.

The same is done for temperature indicators. Much warmer condition than Holocene's average is marked dark red, slightly warmer is colored light red, slightly colder light blue and much colder conditions than average is colored dark blue.

The colors are transferred to a map to get an overview of the climate situations of SA. Each sample site at each time period relates to a color. Each symbol which represents a climate variable.

Figure 7 gives an overview of sample locations, which are taken into account in this thesis. Some sample sites are located very close to each other. These sample sites are slightly shifted, to make each point visible. Exact sample location's coordinates can be found in table one to three.

Figure 7: Locations of used data sets in SA.

Table 1: Details of the used temperature data

	CONTRIBUTORS	NAME OF DATA SET	LAT	LON	Region	ARCHIVE	PROXY
Temperature	Lea, D. W. et al. 2003	Cariaco Basin (PL07-39PC)	11	-66	Cariaco Basin	paleocean	Mg/Ca
	Thompson, L.G. et al. 1995	Huascarán Ice Core Data	-9	-78	Peruvian Andes	ice core	NO3-
	Thompson, L.G. et al. 1995	Huascarán Ice Core Data	-9	-78	Peruvian Andes	ice core	dO18
	Thompson, L.G. et al. 1998	Sajama 1997 Ice Core, Bolivia	-18	-69	Bolivian Altiplano	ice core	Cl-
	Thompson, L.G. et al. 1998	Sajama 1997 Ice Core, Bolivia	-18	-69	Bolivian Altiplano	ice core	d18O
	Thompson, L.G. et al. 1998	Sajama 1997 Ice Core, Bolivia	-18	-69	Bolivian Altiplano	ice core	NO3-
	Thompson, L.G. et al. 1998	Sajama 1997 Ice Core, Bolivia	-18	-69	Bolivian Altiplano	ice core	SO4--

Table 2: Details of the used precipitation data

	CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PROXY
Precipitation	Crutis, J.H. et al. 1999	Lake Valencia, Venezuela Stable Isotope and Carbonate Data (16-VII-94)	10	-68	Venezuela	lake sediments	CaCO3
	Haug, G.H. et al. 2001	Cariaco Basin Trace Metal Data	11	-65	Caribbean Sea	sea sediment	Titanium
	Fritz, S.C. et al. 2003	Salar de Uyuni Drill Hole Natural Gamma Radiation Data	-16	-69	Altiplano	lake sediment	benthic
	Fritz, S.C. et al. 2004	Salar de Uyuni Drill Hole Natural Gamma Radiation Data	-20	-67	Altiplano	lake sediment	gamma (c.p.s)
	Fritz, S.C. et al. 2004	Salar de Uyuni Drill Hole Natural Gamma Radiation Data	-16	-69	Altiplano	lake sediment	freshwater planktonic
	Fritz, S.C. et al. 2005	Salar de Uyuni Drill Hole Natural Gamma Radiation Data	-16	-69	Altiplano	lake sediment	Salinity Indifferent Planktonic
	Fritz, S.C. et al. 2006	Salar de Uyuni Drill Hole Natural Gamma Radiation Data	-16	-69	Altiplano	lake sediment	Saline Planktonic
	Lin, H.L. et al. 1997	Cariaco Basin Stable Isotope Data (PL07-39PC)	10	-65	Caribbean Sea	paleocean	delta O18 PDB (Globigerina bulloides)
	Lin, H.L. et al. 1998	Cariaco Basin Stable Isotope Data (PL07-39PC)	10	-65	Caribbean Sea	paleocean	delta O18 PDB (Globigerinoides ruber (white))
	Lin, H.L. et al. 1999	Cariaco Basin Stable Isotope Data (PL07-39PC)	10	-65	Caribbean Sea	paleocean	delta O18 PDB (Neogloboquadrina dutertrei)
	Moy, C.M. et al. 2002	Digitised data from Fig.4B: d18Ocalcite - d18Oice (Huascarán)	-3	-79	Laguna Pallcacocha	lake sediments	Red Color Intensity Units

Table 3: Details of the used precipitation data

	CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PROXY
Precipitation	Peterson, L.C. et al. 2000	Tropical Atlantic hydrologic cycle during the last glacial	12	-61	Caribbean Sea	sea sediment	Percent reflectance on the 550nm wavelength
	Rein, B. 2007	El Nino activity in the past.	-13	-78	Coast of Peru	sea sediment	lithic concentrations
	Rodbell, D.T. et al. 1999	Ecuador Alluvial Sediment Gray Scale Data	3	-79	Eastern Eq. Pacific	lake sediments	grey scale (0-256)
	Seltzer, G. et al. 2000	Isotopic evidence in tropical South America	-11	-77	Andean	lake sediments	Dd18Ocalcite-ice‰ (VPDB)
	Thompson, L.G. et al. 1998	Sajama 1997 Ice Core, Bolivia	-18	-69	Bolivian Altiplano	ice core	dust particles
	Thompson, L.G. et al. 1995	Huascarán Ice Core Data	-9	-78	Peruvian Andes	ice core	dust particles

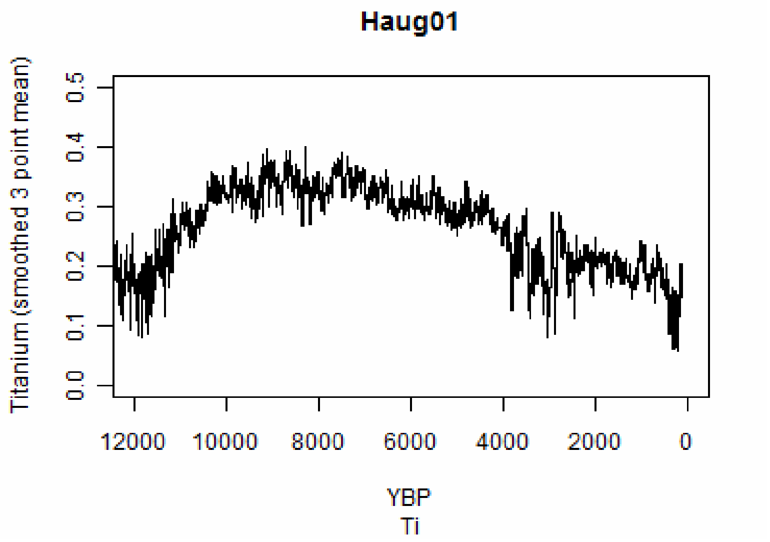

Figure 8: Time series of the smoothened titanium concentrations in the Cariaco Basin, contributed by Haug et al. (2001)

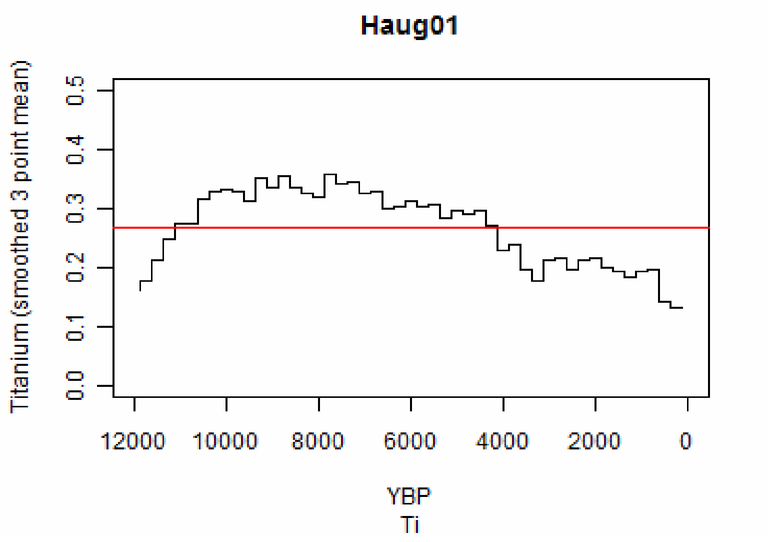

Figure 9: Classified time series of the smoothened titanium concentrations in the Cariaco Basin, contributed by Haug et al. (2001). The red line indicates the mean classified value of the last 12,000 years.

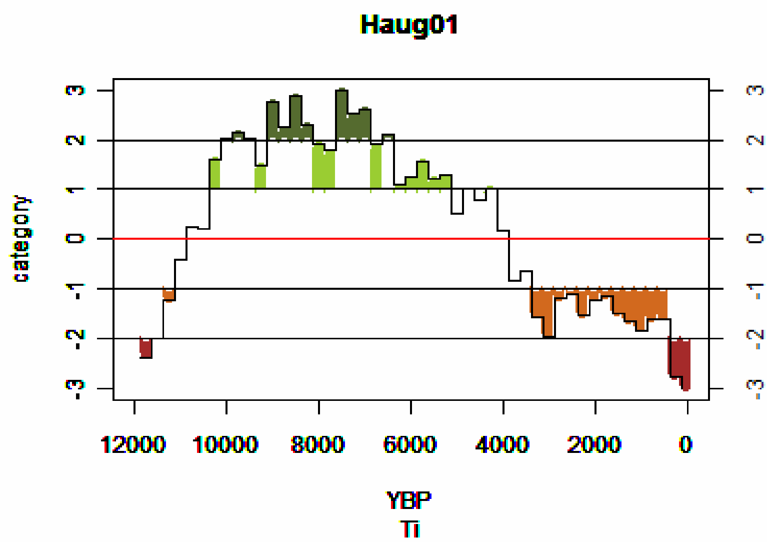

Figure 10: Categorized and classified time series of smoothed titanium concentrations in the Cariaco Basin, contributed by G.H. Haug. The red line indicates the mean classified value of the last 12,000 years. Dark green (> 2) indicates much wetter conditions than the Holocene average. Light green (< 2 and > 1) indicates slightly wetter conditions, light brown (< -1 and > -2) indicates slightly dryer conditions and dark brown (< -2) marks strongly dryer conditions than the average of the last 12,000 years.

3. Results

3.1 Precipitation

To analyze SA precipitation during the Holocene, all data is drawn in one box plot (Figure 11).
At the beginning of the Holocene, no clear trend can be determined. The spread of the category values is decreasing toward present. During the Holocene period, most classes' mean value is between minus one and plus one. Only the last 3,000 years of the Holocene are out of this range. Eleven of twelve classes have mean category values lower than minus one. This drying trend already started at 4,500 yBP and hold on until present. To gain more precise precipitation information, data of different climate regions is distinguished.

The Andes were dry during the first 4,000 yBP of the Holocene (Figure 12). The following 750 years were wetter in average followed again by dry conditions. Then, the conditions turned to be wet at 5,000 yBP. Subsequently the situation turned to dry once more. After 2,500 yBP more or less steady dry conditions exist until the present. Notable is the dry period between 1,750 yBP and 3,000 yBP, in which all data of four of the five classes is clearly dryer than the Holocene average. The scattering range has become narrower from the beginning of the Holocene to present. Especially the wide scattering range of the class 12,000 to 11,750 yBP is remarkable.

In contrast to the Andes, the Caribbean started with extreme wet conditions around 12,000 yBP, compared to the Holocene's average (Figure 13). Beginning 12,000 yBP and lasting up to the present the climate gradually changed to dryer conditions with the exception of some outliers, such as the one at 6,000 yBP. Remarkable is a very narrow value range between 1,500 yBP and 3,750 yBP, clearly indicating conditions much dryer then the Holocene's average.

At the west side of the Andes, only one core is available from a shelf, which is located 80 km from Lima. Figure 14 shows the classified and categorized values of this core. This data set starts with very wet conditions followed by an abrupt change to very dry conditions. In contrast to the Andes and the Caribbean, the general trend in the middle Holocene is a change of climatic conditions from dry to wet. The wettest condition prevailed at 3,250 yBP. After this date, the conditions change initially slowly and then abruptly to the end to very dry conditions. During the last 500 yBP the climate turned to be a little wetter again, but it is still dry if compared to the Holocene's average. The dry end of the Holocene is also observed in the Andes and in the Caribbean. West of the Andes began the dry period later than in the other two regions. The significant dry period in the Andes, between 3,000 and 1,750 yBP and in the Caribbean between 3,700 and 1,500 yBP, respectively, are not observed in the single core west of the Andes.

Figures 15a, b and c show each proxy value for each time period on the SA map. Circles stand for precipitation. Brown indicates dry conditions and green wet conditions. White circles indicate climatic conditions, which are close to the Holocene's average (see chapter 2.1). It becomes evident from looking at the maps that the north Andes were dryer than the middle Andes during the last 4,250 yBP.

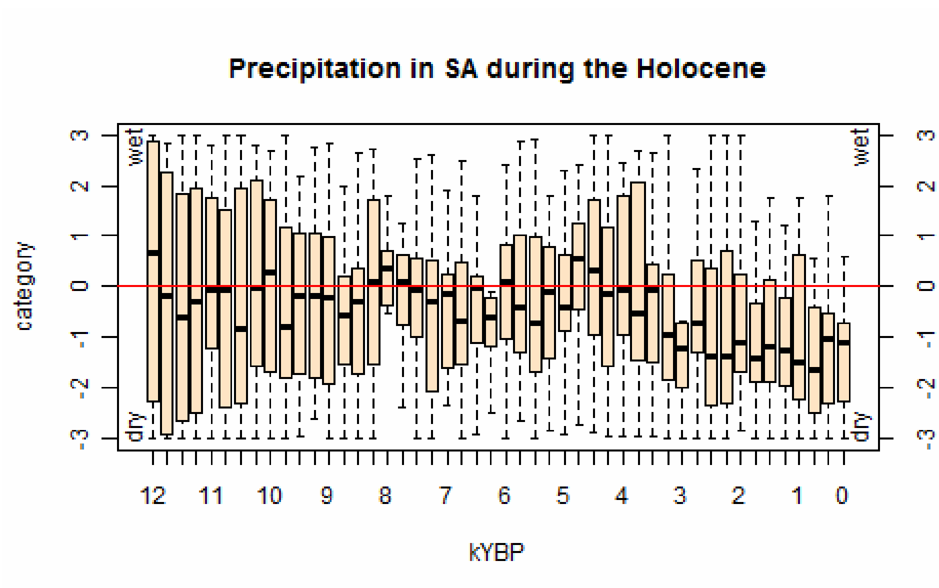

Figure 11: Box plot of precipitation in SA during the Holocene.

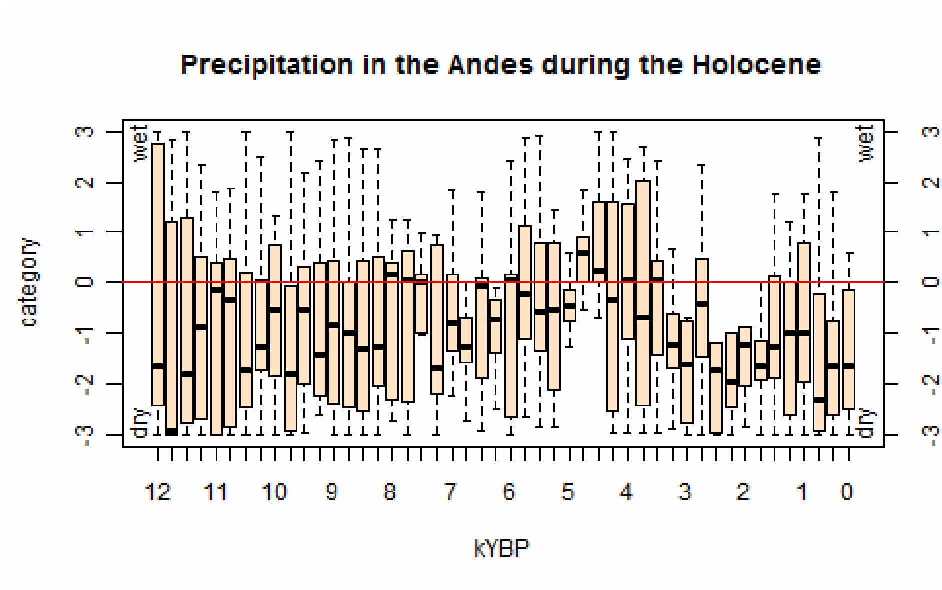

Figure 12: Box plot of precipitation in the Andes during the Holocene.

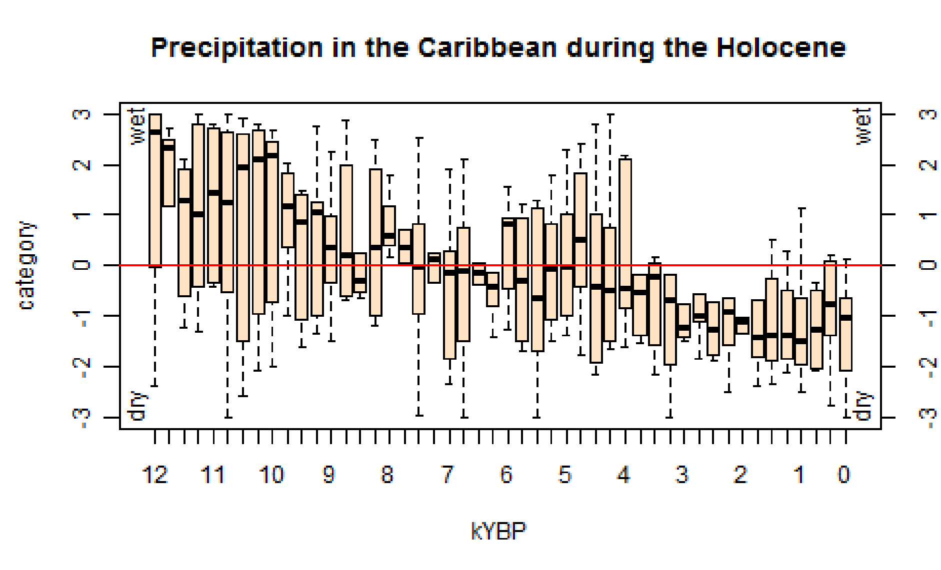

Figure 13: Box plot of precipitation in the Caribbean during the Holocene.

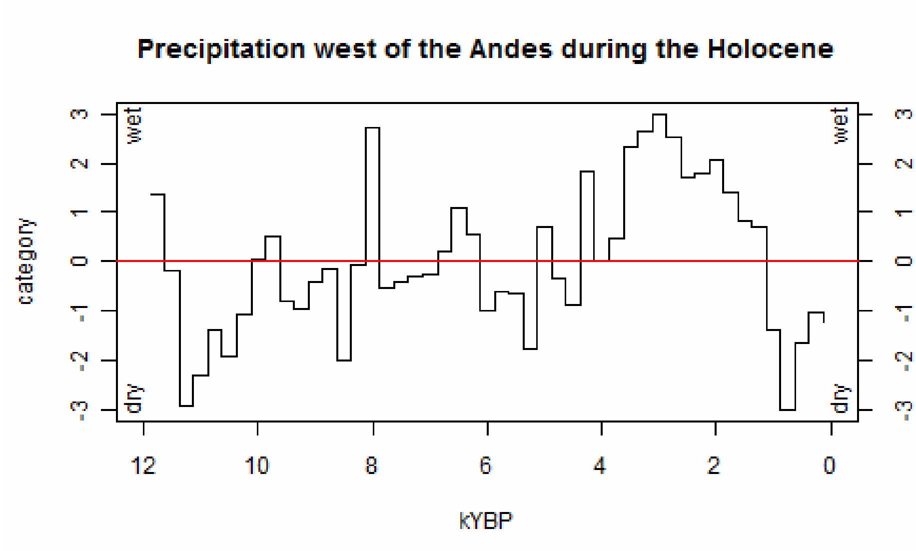

Figure 14: Categorized and classified time series of smoothed lithic concentration at a shelf, which is located 80 km off Lima, contributed by Rein B. 2007.

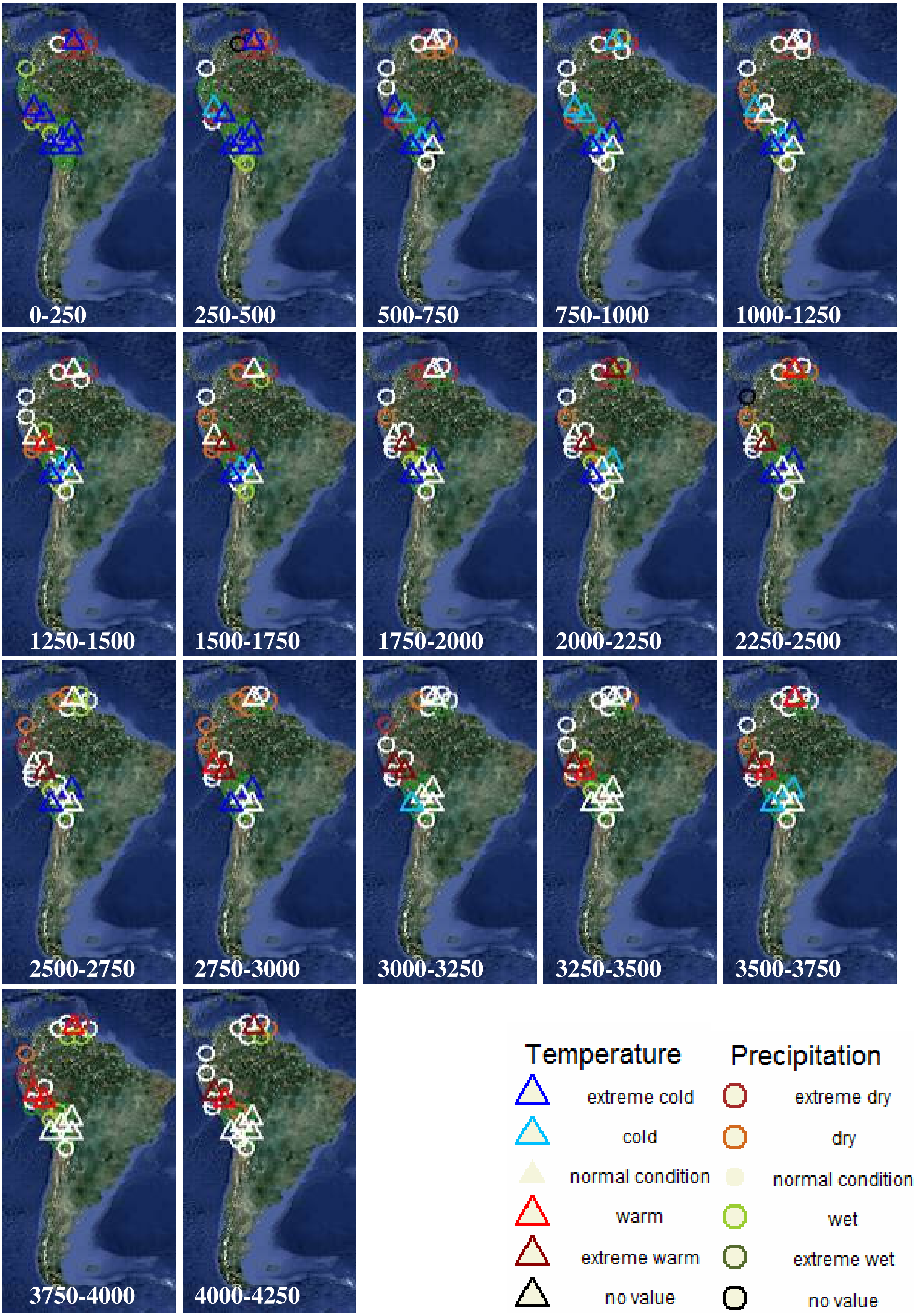

Figure 15 a: Climatic conditions at time classes from the present to 4,250 yBP. Triangles indicate temperature proxies and circles precipitation. Brown indicates dryer conditions and green wetter conditions than the average of the Holocene. Blue indicates low temperatures and red warmer temperatures respective to the Holocene's average.

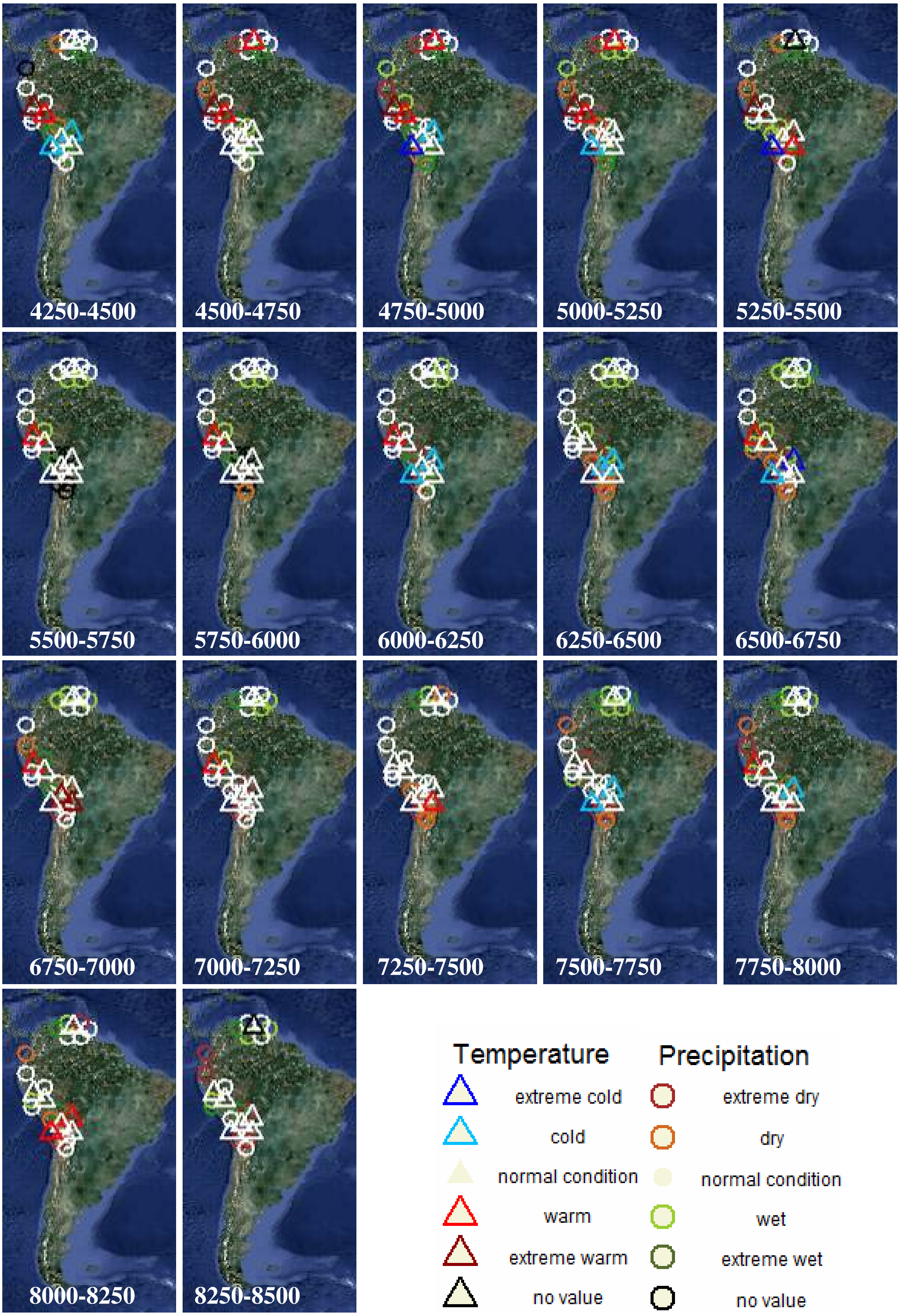

Figure 15 b: Climatic conditions at time classes from 4,250 to 8,500 yBP. Triangles indicate temperature proxies and circles precipitation. Brown indicates dryer conditions and green wetter conditions than the average of the Holocene. Blue indicates low temperatures and red warmer temperatures respective to the Holocene's average.

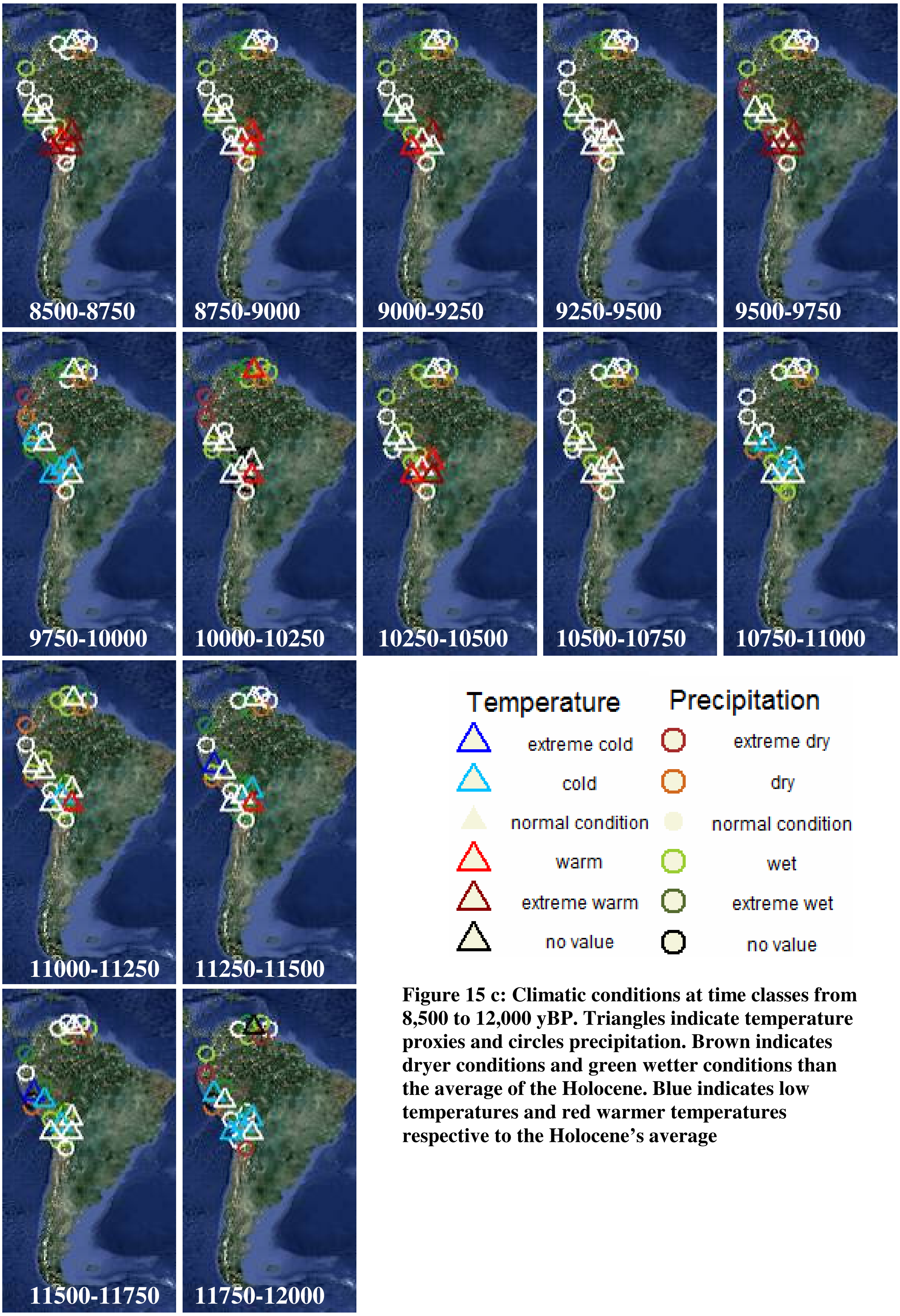

Figure 15 c: Climatic conditions at time classes from 8,500 to 12,000 yBP. Triangles indicate temperature proxies and circles precipitation. Brown indicates dryer conditions and green wetter conditions than the average of the Holocene. Blue indicates low temperatures and red warmer temperatures respective to the Holocene's average

3.2 Temperature

In SA, the Holocene started with cold conditions and a strong, steady temperature rise until 9,500 yBP (Figure 16). The temperature then rose to a warm level during the following 1,500 years. Next, the temperature fell until 5,250 yBP. An abrupt change to warm conditions appeared between 5,250 and 4,500 yBP. Then, the temperature dropped at 4,500 yBP followed by another temperature increase, which ended at 3,250 yBP. From that date on, the conditions were a little warmer than the Holocene's average. One exception is found in the class 2,250 yBP. In this class all available classified data shows cold conditions. At 1,500 yBP, the temperature dropped strongly and stayed on a cold level up to the present. Note, that all data sets, except of one, origin from the Andes from two locations. That is the reason that figures 16 and 17 do not differ significantly.

Figure 18 shows the separated core of the Caribbean. The Holocene's temperature started very low and increased until 7,750 yBP. During the following thousands of years the values fluctuate around normal conditions. Some values are missing. The predominant temperature conditions at the end of the Holocene correspond to Holocene's average temperature.

Figure 15 a, b and c show each core at each time period. Triangles correspond to temperatures. Blue indicates cold and red warm conditions. White triangles indicate normal conditions, compared to the Holocene's epoch (see chapter 2.1). Between 9,750 yBP and 8,500 yBP, the cores located in the middle Andes show significant warmer conditions than in the northern Andes. The opposite took place in the years 5,250 yBP to 1,250 yBP, in which the north Andes indicate higher categorized temperatures than the middle Andes.

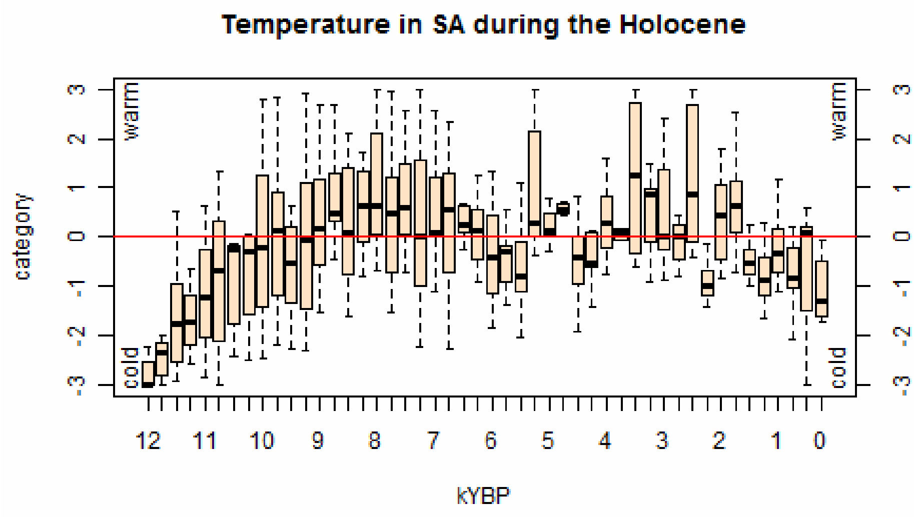

Figure 16: Box plot of temperatures in SA during the Holocene.

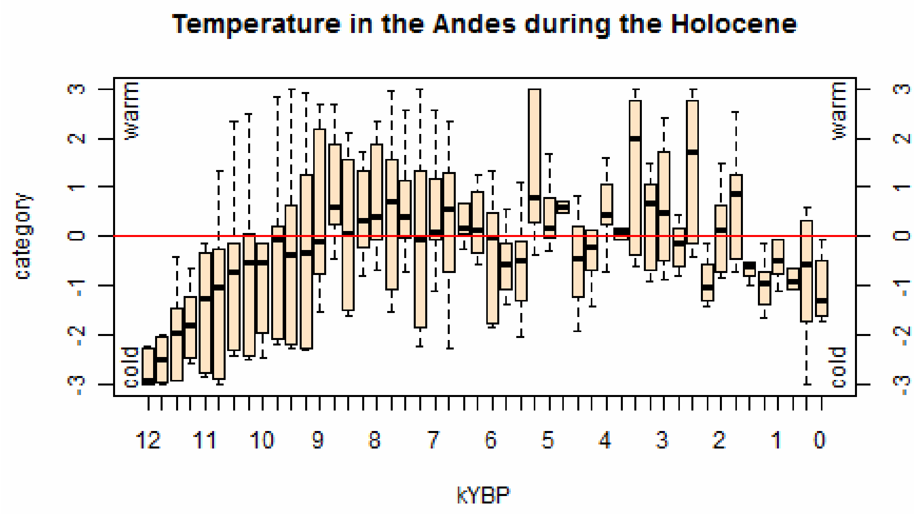

Figure 17: Box plot of temperatures in the Andes during the Holocene.

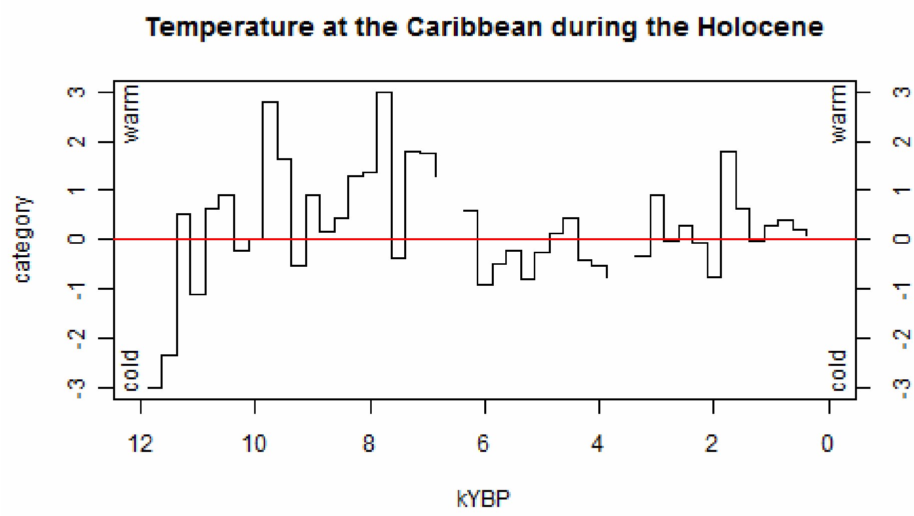

Figure 18: Categorized and classified time series of smoothed Mg/Ca at the Cariaco Basin, contributed by Lea D.W. (2003).

4. Discussion

The papers belonging to the used data sets confirm our results.

The **Caribbean region**'s wettest condition occurred between 10,500 yBP and 5,400 yBP (Haug et al. 2001). The same pattern is observed in Venezuela. The early and mid- Holocene is characterized by wet conditions, while the last 3,000 years tend to drier conditions (Curtis et al. 1999). In the Little Ice Age (LIA), the Caribbean region registered dry conditions (Haug et al. 2001).

In the **Andes**, a dry period is observed between 9,000 yBP and 3,000 yBP (Thompson et al. 1998). Seltzer et al. (2000) report an arid phase in the late Glacial and early Holocene, followed by wet conditions in the middle and late Holocene. They found a continuous trend toward wetter conditions during the past 10,000 years. At Lake Titicaca, wet conditions prevailed between 10,000 yBP and 8,000 yBP, between 7,500 yBP and 6,500 yBP and again between 4,000 yBP and the present. In the middle Holocene extreme arid conditions dominated (Tapia et al. 2003). Not all of these results could be confirmed by our findings. The consensus of these studies in the Andes is low, which can also be seen in the wide mandatorily scattering range of our results (Figure 11).

Other studies expect a steady increase in precipitation between 4,000 yBP and 2,400 yBP and again during the LIA at the Lake Titicaca (Baker et al. 2001). An arid period is also found between 8,600 yBP and 6,400 yBP (Moreno et al. 2007). Grosjean et al. 2001 suggest a wet late Glacial and early Holocene, a dry event around 10,000 ^{14}C yBP, an arid mid-Holocene, followed by wetter conditions at Lake Titicaca. The dry event around 10,000 ^{14}C yBP is expected as a regional effect. Mid-Holocene aridity was interrupted by short-lived, abrupt moisture changes, which could also have been a result of individual storms (Grosjean et al. 2001). A next core of Lake Titicaca, which only goes back to 8,000 yBP, shows a major dry event at 2,300 yBP and a dry period around 5,300 ^{14}C yBP. A wet period is found to have occurred between 8,100 ^{14}C yBP and 7,710 ^{14}C yBP (Mourguiart et al. 1998). In the Bolivian Andes a wet phase is observed during the late-Glacial and early Holocene time by Sylvestre et al. (1999).

Thompson et al. (1995) used additional temperature data to analyze the climate. In the Andes warm and moist conditions dominated between 10,000 yBP and 7,000 yBP. Warmest Holocene conditions prevailed between 8,400 yBP and 5,200 yBP with its warmest conditions

between 6,500 yBP and 5,200 yBP. The climate has been cooling after 5,000 yBP with lowest temperatures during the LIA. The past two centuries and especially the past two decades reached the highest values since 3,000 years (Thompson et al. 1995).
To recapitulate, it is likely, that the Holocene started with wet conditions, which also is known as the wet Coipasa event in the central Altiplano, which was dated between ca. 10,500 yBP to 9,500 yBP (Tapia et al. 2003) or between 13,000 yBP to 11,500 yBP (Moreno et al. 2007). Bradbury et al. (2001) described the Coipasa event as a slight oscillation of lake levels. Sylvestre et al. (1999) concluded, that the Coipasa event should be confirmed by further studies. Here, the Coipasa event could not be detected in all studies, but in some of them, depending in which time period the Coipasa event is expected. At the very beginning of the Holocene a wet event was found by Grosejan et al. (2001) and by Sylvestre et al. (1999). Tapia et al. (2003) and Thompson et al. (1995) detected a wet period after 10,000 yBP.
It is generally accepted that the northern and central Andes were predominantly arid between 7,000 yBP and 4,000 yBP (Moreno et al. 2007). This was confirmed by Abbott et al. (1997), Baker et al. (2001), Grosjean et al. (2003), Paduano et al. (2003), Tapia et al. (2003), Thompson et al. (1998), Thompson et al. (2000), Mourguiart et al. (1998) and Núñez et al. (2002). Other studies suggest a period of increased precipitation during the mid- Holocene (Holmgren et al. 2001, Latorre et al. 2003, Servant and Servant-Vilardy 2003).

At **Tierra del Fuego** and **Southern Patagonia** regions, which both are located at high southern latitudes, the Holocene started with wet conditions which lasted until 8,500 yBP, followed by a change to warmer conditions in the east and a change to warmer and dryer conditions in the west. Around 6,000 yBP, precipitation decreased, while between 5,000 yBP and 3,000 yBP the conditions were similar to those before 6,000 yBP with a lot of precipitation, but with less moisture in Southern Patagonia than before. The changed conditions between 6,000 yBP and 5,000 yBP could have been influenced by a major volcanic event, which exactly took place in this time period. Around 3,000 yBP modern climate conditions established (Markgraf 1983).

In the **Mallin Book**, in the **Lago Mascardi-Gutierrez** and in the **Alerce** regions at temperate climate zones, a strong temperature and precipitation decrease was detected between 11,000 yBP and 10,000 yBP. After 8,500 yBP, the temperature increased again and precipitation decreased on the east side of the Andes until 5,000 yBP and on the west side of the Andes up to 6,500 yBP. During the next time period, which ended around 2,500 yBP, the precipitation decreased to the west. Warmer and dryer conditions than today prevailed at the west side of the Andes, while moist climate dominated at the east side (Markgraf 1983).

The arid region of **Mendoza Province** was analyzed by pollen data. At 12,000 yBP, a shift from winter rain dominated climate to modern summer rain dominated climate and modern temperatures was found. Between 8,500 yBP and 5,000 yBP the summer precipitation decreased and the temperature increased. From 5,000 yBP to 3,000 yBP precipitation increased, presumably induced by winter rains. The temperatures were lower. From 3,000 yBP, modern conditions prevailed with summer rains in lowlands and more favorable temperatures in the uplands (Markgraf 1983). At the mid-Chilean coast side, an aridity is detected during the early and the mid-Holocene and is most pronounced during mid-Holocene. The late Holocene is marked by a change from arid to more humid conditions (Mohtadi et al. 2004). In northern Chile, the continental humidity effect increased (McGlone et al. 1992).

In the **South Brazilian highlands** the early and mid-Holocene conditions were warm and perhaps wetter compared to late-Glacial conditions (Behling 1997). Seltzer et al. (2000) suggest colder and drier conditions prevailing in the late-Glacial and early Holocene in southeast Brazil. The late Holocene is marked by wetter climate conditions and shorter dry seasons. In the last 1,500 years a climate with high precipitation and without a strong dry season established (Behling 1997).

At the **southern margin of Amazonia**, pollen records show a southward expansion of humid evergreen forest during the late Holocene (Mayle et al. 2000).

In the mid-Holocene, the conditions were wet in Mexico, Guatemala, Panama and Costa Rica (Crutis et al. 1999, Harrison et al. 2003).

Figure 19 gives an overview of some general structures of Holocene climate in SA. Red indicates warm, blue stands for cold conditions. Brown stands for dry and green for wet conditions, respectively.

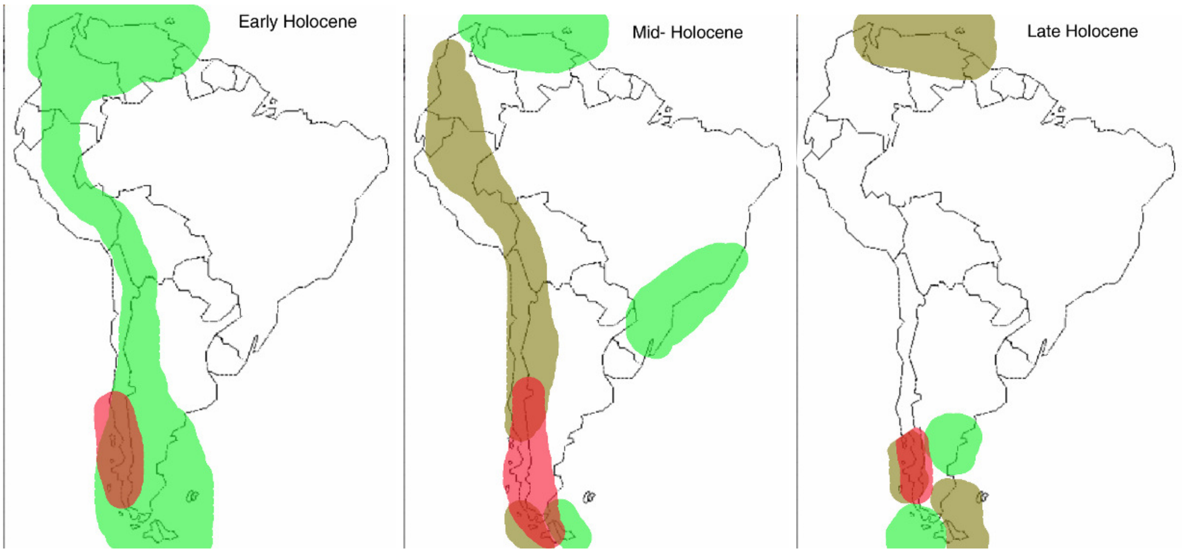

Figure 19: Synthesis of Holocene's climate condition. Profiles are taken from http://aufenthaltstitel.de/staaten/suedamerika.gif

At most locations the Holocene climate of SA started with wet conditions, the so-called Coipasa phase, as mentioned before. In former studies it was assumed that these wet conditions were a result of deglaciation. More recent studies state that this hypothesis is highly unlikely, due to the advancement of the glaciers close to paleolakes after ca. 13,300 ^{14}C yBP. It is suggested, that the glaciers advanced due to increased summer moisture (Clayton et al. 1997). The Coipasa phase correlates with Youger Dryas (Backer et al. 2001).

Cooling in Younger Dryas is found in the Chilean lake region (Moreno 1997) and in fossil coral reefs from offshore Barbados (Guilderson et al. 2001, Peltier and Fairbanks 2006). The island of Barbados is located in the eastern Caribbean Sea. The end of the YD in Barbados does not coincide with the YD end in Europe (Fairbanks 1990, Rühlemann et al. 1999). In this study the Younger Dryas is also found. It is remarkable, that the temperature increase at the beginning of the Holocene hold until 9,500 yBP, what is quite long compared to literature.

The Little Ice Age (LIA) is a cold phase, which is well known in Europe and in North America. The Yucatan Peninsula and other circum-Caribbean paleoclimate records indicate colder SSTs and aridity in the beginning of the LIA (Hodell et al. 2005). Our results confirm the known cold phase during the LIA. The present warming and the end of the LIA can not be distinguished in the last class of this study. However, the present anthropogenic warming can be seen in the scattering range and in the reduced cold conditions at the end of the LIA. If

100 year classes are built, instead of the here used 250 year classes, the cooling of LIA and the present warming becomes clearly visible (Thompson et al. 1995).

During the Holocene a general southward shift of ITCZ is believed. Change in seasonality of insolation is also affected by this shift (Wanner et al. 2008). It is also possible, that the ITCZ shift is associated with the 21,000 year precession component of Milankovitch forcing. During the late Holocene, Southern Hemisphere insolation became more seasonal, while the Northern Hemisphere insolation became less seasonal (Berger and Loutre 1991). As the ITCZ moved southward from the equator, summertime rainfall dropped near the Cariaco Basin, while rainfall increased over the Amazon (Mayle et al. 2000, Maslin and Burns 2000). This pattern was observed in the Cariaco Basin by Haug et al. (2001). A slight shift of the southern Atlantic ITCZ is also shown by models (Harrison et al. 2003). Crutis et al. (1999) link the wet conditions in the early to mid-Holocene in the Cariaco Basin with the shift of the ITCZ. They claim that an increased intensity of the annual cycles with wetter rain seasons and drier dry seasons in Valenzia as well as in the northern Neotropics were caused by the strong annual shift of the ITCZ. In the past 3,000 years Crutis et al. (1999) observed a reduction of the annual's cycle intensity, probably caused by a reduction of the annual oscillation of the ITCZ between north and south. It results in dryer conditions in northern SA and in the circum-Caribbean region (Crutis et al. 1999). Another study also confirms the southward shift of the ITCZ. An anticorrelation of precipitation in Cariaco and southern margin of the Amazons is found during the Holocene, which correlates to the assumed Holocene ITCZ movement pattern (Mayle et al. 2000, Haug et al. 1999).
In contrast, Moreno et al. 2007 believe that a dry period at Cariaco Basin is related to a northward displacement of the ITCZ. A northward shift of ITCZ also causes enhanced precipitation in Central America and American's southwest and has a negative feedback effect on the monsoonal precipitation in northern SA (Harrison et al. 2003).

Other studies link the ITCZ with the monsoon, but in a larger scale. Tapia et al. (2003) conclude that, during the early and mid-Holocene, the increased precipitation in the Altiplano and monsoonal activity in the northern tropics probably caused enhanced precipitation by more advection of moisture from the Amazon Basin. This is induced by the southerly displacement of ITCZ. Grosjean et al. (2001) also suggested that wet late Glacial and early Holocene conditions were caused by strengthened tropical summer precipitation with continental moisture originating from the Atlantic.

Markgraf (1983) detected larger temperature gradients between land and ocean caused by reduced amplitudes of seasonal insolation cycles. She assumed that this pattern strengthens the summer and winter monsoons in the Northern Hemisphere and weakens the summer and winter monsoons in the Southern Hemisphere.

Further, the precipitation pattern in SA correlates with Southern Hemisphere circulation anomalies. If the latitudinal position of the subtropical high pressure cell over the South Atlantic is located near the equator, the precipitation increases in central Chile and eastern Patagonia. If this cell is located at somewhat higher latitudes, more precipitation than normal occurs in North Chile and Southwest Patagonia. Next, the position of the circumpolar low pressure belt influences the precipitation pattern of SA. The circumpolar low pressure belt is expressed as the transpolar vortex. If the vortex is positioned close to SA, higher than normal precipitation prevails in central Chile and Argentina and in Southeast Patagonia. If the vortex is close to Australia, higher than normal precipitation occurs over northern Argentina only.
In the early Holocene, the conditions were similar to today's conditions in southern SA. The conditions were temperate at 41°S and arid with summer rain at 34°S. The subtropical high pressure cell was shifted towards the equator, the circumpolar vortex remained displaced towards Australia. After 8,500 yBP, at 41°S the climate was more continental with colder winters and drier summers. The summer rain decreased at 34°S . The subtropical high pressure cell was positioned closest to the equator, while the circumpolar vortex moved toward SA. In the mid-Holocene, precipitation decreased in high southern latitudes and the conditions turned to arid. The circumpolar vortex moved back to Australia and the subtropical pressure cell remained in closest to the equator. Between 5,000 yBP and 3,000 yBP precipitation increased again between 51-54°S and 31-34°S and at 34°S especially the winter rain increased. The subtropical high pressure cell moved to lower latitudes and the circumpolar vortex shifted back towards SA. After 3,000 yBP, at all latitudes, precipitation decreased and temperature increased to modern conditions. At 31-34°S a shift occurred from winter rain to summer rain pattern and the eastern lowlands became arid. The high pressure cell shifted away from the equator to the polward position and the circumpolar vortex moved back towards Australia. All precipitation patterns at all latitude in southern SA are not as clearly defined as during the earlier Holocene periods. The assumed present higher climate variability could be a result of higher frequency of shifts of circulation anomaly patterns from one extreme to the other (Markgraf 1983).

In Brazil, a feedback between positive SST anomalies and a weak SACZ may enhance the LLJ which increases moisture contribution into southern Brazil. It shows a positive association between SAM activity and SST in the western subtropical South Atlantic (Doyle and Barros 2002).

From 8,600 yBP to 6,400 yBP the most arid period is detected in the Altiplano region. Further south at Lake Titicaca the most arid period is assumed between 6,000 yBP and 5,000 yBP. Moreno et al. 2007 conclude that this phenomena could imply a stronger north-south gradient in the Andes (Moreno et al. 2007)

Mohtadi et al. (2004) found a southward sift of the climate zones, i.e. the Southern Westerlies and the circum-Atlantic conditions, which caused the aridity during the early and the middle Holocene on the Chilean coast. Southern and central Chile climate is strongly related to the Southern Westerlies (Mohtadi et al. 2004). Markgraf (1993) states that the arid period in central and northern Chile generally occurs due to a stronger influence of the southeast Pacific high pressure cell blocks the westerly front systems. The Southern Westerlies shifted between 10,000 yBP and 5,000 yBP to higher latitudes and a seasonal shift of the Westerlies, as under modern conditions, did not develop during this time period. During the late Holocene, the conditions changed form arid to more humid at the Chilean coast (Mohtadi et al. 2004). It is expected, that a northward shift of the Westerly belt, which is no more blocked by the high pressure belt, leading to positive rainfall anomalies in central and northern Chile. High rainfalls off Peru and arid coastal lowlands result from southward and eastward invasions of warm air masses. These conditions brought high precipitation in central and northern Chile, Peru and Ecuador during the late Holocene and are indicators of intense El Niño (Mohtadi et al. 2004). This statement is confirmed by other studies (Moy et al. 2002; Rein 2007). The ENSO event frequency increased from the beginning of the Holocene to the present (Moy et al. 2002, Rein 2007). In the early Holocene, the ENSO was weak or nonexistent (Moy et al. 2002), while probably the ENSO became more intense within the last 5,000 years (Mothadi et al. 2004).

Cruz et al. (2005) suggest a rapid northward shifts in the mean location of the SA-monsoon causing a rapid increase in the methane concentration during the Holocene. In this situation, the centre of convective activity related to the SASM was probably displaced northward. In general the movement of the monsoon intensifies the mean zonal Hadley circulation. Additionally, the YD correlates with the rapid southward movement of SA monsoon (Cruz et al. 2005).

Natural forcing could also be a reason for changed climate in SA. For example, the volcanic activity in the Andes reduced the temperature (Thompson et al. 1998).

Around 8,000 yBP world-wide flooding events occurred, that could be related to the dry mid-Holocene. In this study, such global teleconnections were not taken into account (Mourguiart et al. 1998).

5. Conclusion and Outlook

The Holocene started with wet conditions of most regions in South America. A mid-Holocene aridity was observed in the Andes. A wet mid-Holocene is observed between the east coast of southern South America and middle South America as well as in the Caribbean area. During the late Holocene, the Caribbean is assumed to have been dry. Results presented here suggest a dry late Holocene while other studies suggested a wet late Holocene (Baker et al. 2001, Tapia et al. 2003, Seltzer et al. 2000). This conclusion dealing with climatic conditions during the Holocene illustrates the main problem of this study. Only little data of Mexico, Central America and South America is available. The amount of data is insufficient to get an accurate overview of the Holocene climate (Harrison et al. 2003). Especially temperature proxies are rare. Some temperature patterns were found in SA, but all of them are base on one long-term data set only. Furthermore, some data sets were sampled to analyze a much longer time period than just the Holocene. The resolution of this data was insufficient to analyze detailed Holocene patterns. However, more data would be needed to gain higher confidence. This brings us to the next problem: Archive data do not exist in some climatic regions.
Generally, for all of SA further data would be needed to improve the current knowledge and to gain any understanding on the prevailing Holocene climate.

In the discussion paragraph of this study different possible climatic patterns are listed. An unique accurate pattern is not possible to determine due to missing and controversial data of the various studies.

The method of this study could be improved. Neither the mean value of the Holocene nor the mean value of the class 0-250 yBP are good reference values. If using the mean value of a data set, just few missing values are allowed, so that the mean value is not adulterated. The last class of the data set does not give a statistically representative value. In many cases just very few data points, or even worse, no values at all were available in the last class. Ideally, a method should be found, which could also take data sets into account covering just a part of the Holocene.

Finally, this work provides an overview of today's knowledge of temperature and precipitation in SA during Holocene for further paleoclimate research.

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Appendix: Not used Data sets in SA

CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PUBLICATION
Behling, H. 1993	Serra da Boa Vista	-27	-49	South Brazil	Pollen	Untersuchungen zur spätpleistozänen und holozänen Vegetations- und Klimageschichte der tropischen Küstenwälder und der Araukarienwälder in Santa Catarina (Südbrasilien). Dissertationes Botanicae **206**. Berlin Stuttgart, Germany.
Behling,H 1993	Serra do Rio Rastro	-28	-42	South Brazil	Pollen	Untersuchungen zur spätpleistozänen und holozänen Vegetations- und Klimageschichte der tropischen Küstenwälder und der Araukarienwälder in Santa Catarina (Südbrasilien). Dissertationes Botanicae **206**. Berlin Stuttgart, Germany.
Behling,H 1997	Serra Campos Gerais	-24	-50	South Brazil	Pollen	Late Quaternary vegetation, climate and fire history in the Araucaria forest and campos region from Serra Campos Gerais (Paraná), S Brazil. Review of Palaeobotony and Palynology **97,**109-121.
Behling,H. 1993	Morro da Igreja	-28	-49	South Brazil	Pollen	Untersuchungen zur spätpleistozänen und holozänen Vegetations- und Klimageschichte der tropischen Küstenwälder und der Araukarienwälder in Santa Catarina (Südbrasilien). Dissertationes Botanicae **206**. Berlin Stuttgart, Germany.
Behling,H. 1995	Lago do Pires	-17	-42	South Brasil	Pollen	A high resolution Holocene pollen record from Lago do Pires, SE Brazil: Vegetation, climate and fire history. Journal of Paleolimnology **14,** 253-268.
Behling,H. 1996	Lagoa da Curuça	0	-47	Amazon	Pollen	First report on new evidence for the occurrence of Podocarpus and possible human presence at the mouth of the Amazon during the Late-glacial. Vegetation History and Archaeobotany **5,** 241-246.
Behling,H. 1997	Morro de Itapeva	-22	-45	South Brazil	Pollen	Late Quaternary vegetation, climate and fire history from the tropical mountain region of Morro de Itapeva, SE Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology **129,** 407-422.
Cruz, F.W et al. 2005	Botuverá Cave, Brazil Stalagmite Stable Isotope Data	-27	-49	Amazon	Spelothem Data	Insolation-driven changes in atmospheric circulation over the past 116,000 years in subtropical Brazil. Nature **434**.
Fairbanks,R.G. 1990	Barbados Sea Level and Th/U 14C Calibration	13	-60	Caribbean	Coral	The age and origin of the "Younger Dryas climate event" in Greenland ice cores, Paleoceanography, **5**(6), 937-948.

CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PUBLICATION
Fritz,S.C.et al. 1997	Lake Titicaca 370KYr LT01-2B Sediment Data	-15	-69	Andes	Lake sediment	Quaternary glaciation and hydrologic variation in the South American tropics as reconstructed from the Lake Titicaca drilling project. Quaternary Research **68**, 410–420.
Graf,K. 1992	LAPD 1, Ajata	-18	-69	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Graf,K. 1992	Amarete	-15	-68	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Graf,K. 1992	Chacaltaya 2	-16	-68	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Graf,K. 1992	Cotapampa	-15	-69	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Graf,K. 1992	Cumbre Unduavi	-16	-68	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Graf,K. 1992	Laguna Milloc	-11	-76	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Graf,K. 1992	Río Kaluyo	-16	-68	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Graf,K. 1992	Valle Laguna Victoria	8	-70	Andes	Pollen	Pollendiagramme aus den Anden: Eine Synthese zur Klimageschichte und Vegetationsentwicklung seit der letzten Eiszeit. Physische Geographie **34**. University of Zurich, Switzerland.
Grosjean, M. et al. 2001	A 22,000 14C year BP sediment and pollen record	-23	-68	Andes	Lake sediment	A 22,000 14C year BP sediment and pollen record of climate change from Laguna Miscanti 38S/, northern Chile. Global and Planetary Change **28,** 35–51.
Guilderson ,T.P. et al. 2001	Barbados	13	-60	Caribbean	Coral	Tropical Atlantic coral oxygen isotopes: glacial-interglacial sea surface temperatures and climate change. Marine Geology **172**, 75-89.

CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PUBLICATION
Hansen, B.C.S. et al. 1994	LAPD 1, Laguna Huatacocha	-10	-76	Andes	Pollen	Pollen studies in the Junín area, central Peruvian Andies. Geological Society of America Bulletin **95,** 1454-1465.
Hansen, B.C.S. et al. 1994	Laguna Jeronimo	-11	-75	Andes	Pollen	Late Quaternary vegetational change in the central Peruvian Andes. Palaeogeography, Palaeoclimatology, Palaeoecology **109,** 263-285.
Hansen, B.C.S. et al. 1994	LAPD 1, Laguna Pomacocha	-11	-75	Andes	Pollen	Late Quaternary vegetational change in the central Peruvian Andes. Palaeogeography, Palaeoclimatology, Palaeoecology **109,** 263-285.
Hansen, B.C.S. et al. 1994	Laguna Tuctua	-11	-75	Andes	Pollen	Late Quaternary vegetational change in the central Peruvian Andes. Palaeogeography, Palaeoclimatology, Palaeoecology **109,** 263-285.
Hodell, D.A. et al. 2005	Aguada X'caamal, MEX	20	-89	Central America	Lake sediment	Climate change on the Yucatan Peninsula during the Little Ice Age. Quaternary Research **63**, 109-121.
Hodell, D.A., J. H. Curtis, and M. Brenner. 1995	Lake Chichancanab	19	-88	Central America	Lake sediment	Possible role of climate in the collapse of the Classic Maya Civilization. Nature **375,** 391-394.
Hodell, D.A., J. H. Curtis, and M. Brenner. 1995	Lake Chichancanab	19	-88	Central America	Lake sediment	Possible role of climate in the collapse of the Classic Maya Civilization. Nature **375,** 391-394.
Hodell, D.A., J. H. Curtis, and M. Brenner. 1995	Lake Chichancanab	19	-88	Central America	Lake sediment	Possible role of climate in the collapse of the Classic Maya Civilization. Nature **375,** 391-394.
Hodell, D.A., J. H. Curtis, and M. Brenner. 1995	Lake Chichancanab	19	-88	Central America	Lake sediment	Possible role of climate in the collapse of the Classic Maya Civilization. Nature **375,** 391-394.
Imbrie,J. et al. 1992	Late Quaternary variations in ocean hydrography (SPECMAP)	-31	-38	South Atlantic	Paleocean	On the structure and origin of major glaciation cycles. 1. Linear responses to Milankovitch forcing. Paleoceanography **7,** 701-738.
Markgraf,V	Lago Morenito	-41	-71	Southern South America	Pollen	Valencio, A.A. et al. 1985: Palaeomagnetism,sedimentology, radiocarbon age determinations and palynology of the Llao Llao area, southwestern Argentina (lat. 41°S,long. 71°30'W): palaeolimnological aspects. Quaternary of South America and Antarctic Peninsula **3,** 109-148.

CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PUBLICATION
Markgraf,V	Puerto Eden	-49	-74	Southern South America	Pollen	Ashworth, A.C., V. Markgraf, and C. Villagrán (1991): Late Quaternary climatic history of the Chilean Channels based on fossil pollen and beetle analyses, with an analysis of the modern vegetation and pollen rain. Journal of Quaternary Science **6,** 279-291.
Markgraf,V 1983	Isla Clarence	-54	-71	Southern South America	Pollen	Late and Postglacial vegetational and paleoclimatic changes in subantarctic, temperate, and arid environments in Argentina. Palynology **7,** 43-70.
Markgraf,V 1983	La Mision	-53	-67	Southern South America	Pollen	Late and Postglacial vegetational and paleoclimatic changes in subantarctic, temperate, and arid environments in Argentina. Palynology **7,** 43-70.
Markgraf,V 1983	Lago Mascardi-Gutierrez	-41	-71	Southern South America	Pollen	Late and Postglacial vegetational and paleoclimatic changes in subantarctic, temperate, and arid environments in Argentina. Palynology **7,** 43-70.
Markgraf,V 1983	Mallin Book	-41	-71	Southern South America	Pollen	Late and Postglacial vegetational and paleoclimatic changes in subantarctic, temperate, and arid environments in Argentina. Palynology **7,** 43-70.
Markgraf,V 1985	LAPD 1, Aguilar	-23	-65	Andes	Pollen	Paleoenvironemtal history of the last 10,000 years in northwestern Argentina. Zentralblatt Geologie Palaeontologie **11/12,** 1739-1749.
Markgraf,V. 1987	Vaca Lauquen	-36	-71	Andes	Pollen	Paleoenvironmental changes at the northern limit of the subantarctic Nothofagus forest, latitude 37°S, Argentina. Quaternary Research **28,** 119-129.
Mercer, J.H., and T.A. Ager. 1983	Moreno Glacier Bog	-50	-73	Southern South America	Pollen	Glacial and floral changes in southern Argentina since 14,000 years ago. National Geographic Society Research Reports **15,** 457-477.
Mohtadi, M. et al. 2004	Bulk components, concentration and planktonic foraminifera of sediment	-24	-71	Norther Chile Coast Side	Sea sediment	Changing marine productivity off northern Chile during the past 19 000 years: a multivariable approach. Journal of quaternary science **19**(4), 347–360
Moreno A. et al. 2007	Lago Chungara sedimentary sequence in the northern Andean Chilean Altiplano	-18	-69	Andes	lake sediment	A 14 kyr record of the tropical Andes: The Lago Chungará sequence (18°S, northern Chilean Altiplano). Quaternary International **161,** 4-21.

CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PUBLICATION
Moreno,P.I. 1993	Puerto Octay	-40	-72	Southern South America	Pollen	Vegetation and climate near Lago Llanquihue in the Chilean Lake District. M.S. Thesis. University of Maine, Orono, Maine, USA
Mourguiart, Ph. et al. 1998	Comparison of the reconstructed water depth for cores TD1 and TJ in two different basins of the Lake Titicaca	-16	-69	Andes	Lake sediment	Holocene paleohydrology of Lake Titicaca estimated from an ostracod-based transfer function. Palaeogeography, Palaeoclimatology, Palaeoecology **143**, 51-72.
Oliveira,P.E.	Lagoa das Patas	0	-66	Amazon	Pollen	Colinvaux, P.A. et al. (1996): A long pollen record from lowland Amazonia: forest and cooling in glacial times. Science **274,** 85-88.
Peltier,W.R.	Barbados Coral Extended Last Glacial Maximum Sea Level Record	13	-60	Caribbean	Coral	Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews **25**, 3322-3337.
Ruehlemann, C et al. 1999	Tropical Atlantic Alkenone SST Reconstruction for the last 29,000 years	12	-61	Tropical Atlantic	Paleocean	Warming of the tropical Atlantic Ocean and slowdown of thermohaline circulation during the last deglaciation. Nature **402**, 511 - 514.
Salgado-Labouriau, M.L. 1988	Paramo de Miranda	8	-70	Andes	Pollen	Sequence of colonization by plants in the Venezuelan Andes after the last Pleistocene glaciation. Journal of Palynology **23/24,** 189-204.
Schäbitz,F. 1989	Veranada Pelan	-36	-70	Andes	Pollen	Untersuchungen zum aktuellen Pollenniederschlag und zur holozänen Klima- und Vegetationsentwicklung in den Anden Nord-Neuquéns, Argentinien. Bamberger Geographische Schriften 8. Bamberg, Germany.
Schäbitz,F. 1991	Meseta Latorre	-51	-72	Southern South America	Pollen	Holocene vegetation and climate in southern Santa Cruz, Argentina. Bamberger Geographische Schriften **11,** 235-244.
Schäbitz,F. 1994	Salina Anzoátegui	-39	-63	Southern South America	Pollen	Holocene climatic variations in northern Patagonia, Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology **109,** 287-294.
Street-Perrott, F.A et al. 1989	Alsacia	3	-73	South Columbia	Lake sediment	Global Lake-Level Variations from 18,000 to 0 Years Ago: A Paleoclimatic Analysis. U.S. Department of Energy Technical Report 46, Washington, D.C. 20545. Distributed by National Technical Information Service, Springfield.

CONTRIBUTORS	NAME OF DATA SET	LAT	LON	REGION	ARCHIVE	PUBLICATION
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Inwil, 2010

Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Hämmerli Kathrin

Matriculation number: 05-715-339

Programme: Climate Sciences

Bachelor ☐ Master ☐ Dissertation ☐

Thesis title: A review of multiproxy temperature and precipitation reconstructions for South America during Holocene

Thesis supervisor: Prof. Dr. Heinz Wanner

Prof. Dr. Martin Grosjean

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise.

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Place, date

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Signature