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Article

Holocene Climate Variability of the Central Andes (Peru and Bolivia) Reviewed from $\delta^{18}\text{O}$ Stratigraphy of Ice-Cores

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Abstract

Glacial ice cores are evidence of past environmental conditions through gases and elements trapped inside the drilled material. As Central Andes in the southamerican region are very sensitive to climate changes, a great history of temperature and precipitation variability could be found related to massive Ice Caps. Available oxygen isotope data from glacial ice cores conducted over the last three decades in the Central Andes are reviewed to analyze climate variability over the past seven millennia, a period characterized globally by remarkable climatic stability. The analysis allowed for the identification of climate cycles ranging from secular to millennial in time. These cycles have periods of 1.3, 0.87, 0.67, 0.46, and 0.25 kiloyears (ky.). A series of regional thermal minima and maxima are also defined. This variability in the Andean climate during the mid- and late Holocene is interpreted as being strongly controlled by changes in solar activity, in particular, the forcing of "grand solar minima" is recognized. Likewise, less frequent climate changes could be correlated with Bond cycles and increased or decreased activity of the thermohaline circulation.

Keywords: palaeoclimatology; central andes; past temperatures; holocene; stable isotopes; $\delta^{18}\text{O}$ stratigraphy; spectral analysis

1. Introduction

Recent studies highlight the alarming rate at which Andean glaciers are retreating. Total amount includes a 35% faster (0.7 meters by year) retreat than the global average in the last decade [1]. Caro et al. [2] showed an increase of 12% in annual glacier melt for the Andean catchments driven by a 0.4°C shift in temperature and a 9% reduction in precipitation. This rapid loss underscores the urgency of understanding past climate patterns to predict future changes.

The Central Andes of South America have experienced significant climatic shifts during the Holocene period [3–5]. Sediment cores over lakes have shown aridity and precipitation changes in the Central Andes, suggesting climate patterns to have a major role on the centennial to millennial scales climate changes [6,7].

That millennial or centennial scale are also well documented in glacial ice cores drilled at high elevations, where no anthropic modifications have reached and representative regional weather conditions are presented. The trapped air bubbles and particulate matter within the ice cores could be a preserved record of past gas variability [8] or even anthropic activities [9]. The water content of each layer in the Ice-cores could have an amount of stable isotopes (^{18}O and Deuterium, D) representative of past precipitation and temperatures [10,11].

Thirty years of ice cores in the Central Andes have shed light on key aspects of regional climate evolution at the end of the Pleistocene and the Pleistocene-Holocene transition [12–14], as well as the last millennia (e.g., Eichler et al. [15]).

However, the results obtained for these time intervals have led to insufficient attention being paid to the more recent part of the record, particularly the interval between 7000 years BP and the last two millennia. This interval, characterized by relative climatic stability on a global scale, exhibits significant variability in the stable isotope records of Andean glacial ice.

By reviewing the stable isotope data series with new techniques, such as the Lomb-Scargle spectral analysis [16], hidden periodicities and variability of the so called “stable age” of the mid and late Holocene can be analyzed. Lomb Scargle periodogram has shown great results in the analysis of climate patterns [17,18], linking nowadays meteorological periodicities to regional atmospheric configurations.

The aim of this work is to review and re-analyze the palaeoclimate variability based on the available data. Specifically, this study reconstructs the palaeotemperatures of the last 7 ky. Before Present (BP). The variability is inferred from stable oxygen isotope stratigraphy in two ice cores in the Central Andes of Peru and Bolivia, primarily, and another complementary core with deuterium data.

1.1. Location of the Study Area

The analyzed ice cores are located in the Central Andes Mountains (Figure 1) of Peru and Bolivia. The Central Andes is a region of the Andean range that extends from Huancabamba (Peru) at 5°S to the Colorado River basin in the north of the province of Neuquén (Argentina), at 30°S. This section of the Andes contains some of the highest peaks in the range, including the Nevado Huascarán (the 5th highest peak in the Andes with 6757 m.) and Nevado Sajama (15th highest peak in the Andes with 6542 m.).

The Central Andes, as high mountains, are fully climate driven by the altitude modification of temperature, their tropical position and the Andean barrier to humidity fluxes from the Amazonia and Pacific Ocean. Precipitation (if solid or liquid) is related mainly to changes in latitude of the Inter Tropical Convergence Zone [19,20] and to El Niño Southern Oscillation pattern [21].

In this context, some Ice-cores samples were drilled between 1995 and 2003 in glacial ice caps. The Huascarán ice core, was drilled in the Cordillera Blanca of Peru (-9.269311, -77.497399, 6050 meters above sea level); while the Sajama core was drilled in the Central Volcanic Zone of Bolivia (-18.111102, -68.883429, 6542 m above sea level). The information is complemented by the stable hydrogen isotope series from the Illimani core that was drilled in the Cordillera Real of Bolivia (-16.630903, -67.791498, 6350 m above sea level).

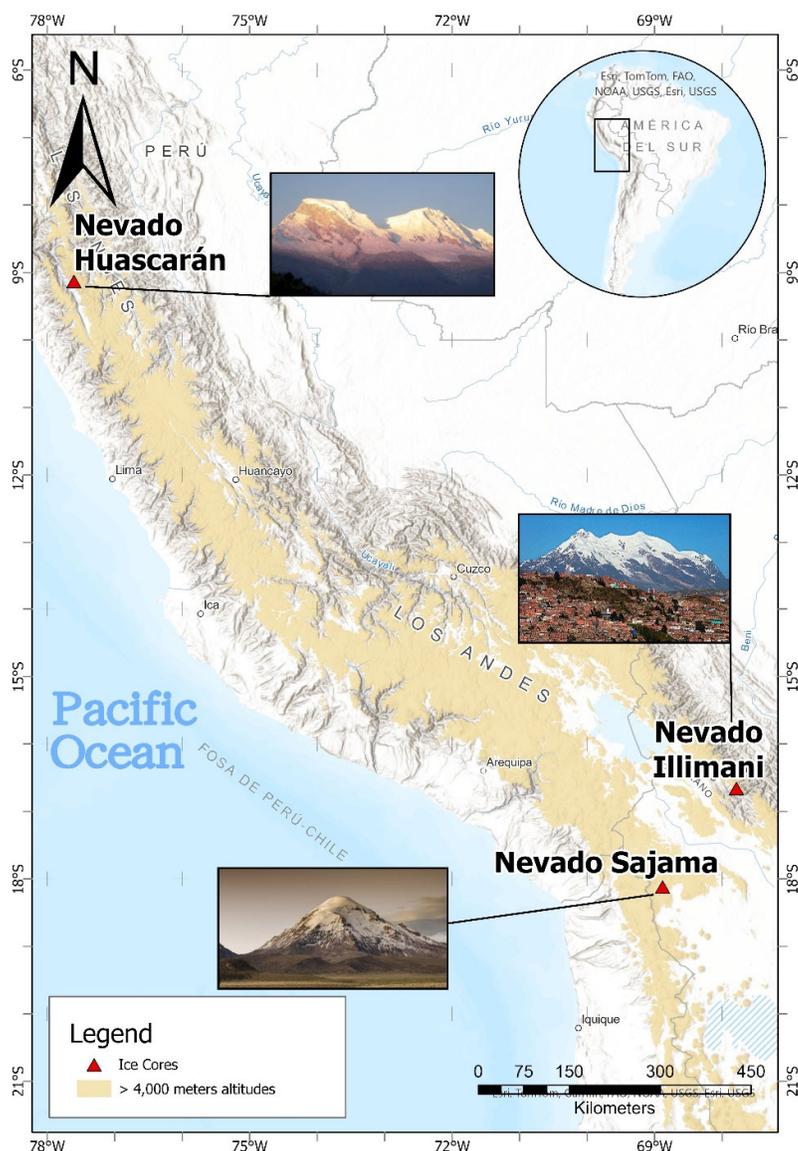


Figure 1. Geographic location of the analyzed Ice-cores. Coordinates are written down in the main text.

2. Materials and Methods

The data from the Huascarán and Sajama cores were extracted from the NOAA (National Oceanic and Atmospheric Administration, USA) repository available at www.noaa.gov. These data correspond to the work of Thompson et al. [12,13]. The Illimani data are taken from Ramírez et al. [14]. The ratio of stable oxygen isotopes $\delta^{18}\text{O}$ and hydrogen δD in glacial ice reflects the isotopic composition of precipitation over the duration of snowfall and, from this, palaeotemperatures can be estimated (e.g., Martín-Chivelet and Muñoz-García or Mc. Dermott [22,23]). The study of $\delta^{18}\text{O}$ (and δD) stratigraphy allows us to analyze relative temperature variations in the intervals considered.

An important aspect is the resolution of the age models on which the time series of these surveys are based. Ice is very plastic, and layer counting (annual stratigraphy), whether visual or geochemical, can only be applied to the most recent levels (the last few centuries). Furthermore, ^{14}C dating of organic remains trapped in the ice, and correlation with other better-dated records, allowed for a more refined dating of the late Pleistocene levels. However, most of the Holocene ice record (between 3,300 and 9,700 years BP in the case of Sajama and essentially the entire Holocene record in

the case of Huascarán) was assigned an age according to a mathematical model. In the case of Illimani, the published age model is based on the correlation of major events (such as the Younger Dryas) with the Sajama survey [14]. The minimum error estimated for all age models is ± 200 years. This significant limitation must be considered in intercomparisons between the series from the two surveys.

To simplify the visual and statistical comparison of the paleoclimate series, the proceeding was to eliminate long-term trends (“detrending”) superimposed on variability on a centennial or millennial scale. To achieve this, a linear fit was used in the case of Sajama and a second-order polynomial fit in Huascarán.

A spectral analysis of the Huascarán and Sajama time series was also performed to identify possible periodic elements in climate variability. For this purpose, the software PAST [24] was used, which works with the Lomb periodogram algorithm [16], which allows obtaining spectral diagrams from time series with non-equidistant values.

3. Results

The Sajama and Huascarán $\delta^{18}\text{O}$ series (Figure 2), which also includes the δD record from the Illimani Ice core, show significant variability. The heaviest $\delta^{18}\text{O}$ values correspond to higher temperatures and vice versa, allowing us to differentiate a series of alternating centennial-scale warming and cooling intervals in each series, as well as a series of episodes of relative minimum and maximum temperatures. A comparative analysis of the series allows us to identify patterns of common variability.

A tentative correlation of the local climatic maxima and minima is therefore established, assuming that they must have been essentially contemporaneous and that, therefore, the small lags between them can be attributed to the models' error margins.

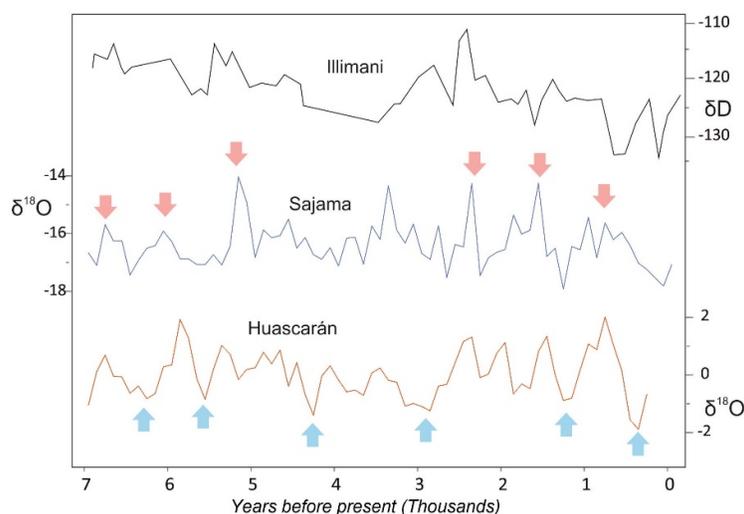


Figure 2. Temporal data series of stable isotopes ($\delta^{18}\text{O}$ and δD) contained in the Illimani, Sajama and Huascarán Ice-cores. Blue arrows indicate main cold episodes, while red arrows indicate maximum temperature episodes.

A total of six climatic maxima and six minima were identified (Tables 1 and 2).

Table 1. Warm episodes identified according to each of the Andean data series. Denomination of each episode is in the main header.

Core/ Warm Episode	Episode VI	Episode V	Episode IV	Episode III	Episode II	Episode I
N. Huascarán	6.4 ky	5.6 ky	5.0 ky	2.2 ky	1.6 ky	0.5 ky
N. Sajama	6.6 ky	5.9 ky	5.0 ky	2.4 ky	1.5 ky	0.7 ky

N. Illimani	6.8 ky	6.0 ky	5.4 ky	2.5 ky	1.4 ky	0.4 ky
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¹ N. meaning "Nevado", Spanish word for "high mountain".

Table 2. Cold episodes identified according to each of the Andean data series. Denomination of each episode is in the main header.

Core/ Cold Episode	Episode VI	Episode V	Episode IV	Episode III	Episode II	Episode I
N. Huascarán	5.9 ky	5.2 ky	4.0 ky	2.6 ky	1.4 ky	0.2 ky
N. Sajama	6.4 ky	5.5 ky	3.9 ky	2.6 ky	1.2 ky	0.1 ky
N. Illimani	6.6 ky	5.7 ky	3.6 ky	2.7 ky	-	0.3 ky

¹ N. meaning "Nevado", Spanish word for "high mountain".

On the other hand, the results of the spectral analysis of the two surveys with the largest amount of data, represented in the spectral diagrams (Figure 3), show notable similarities, with spectral maxima around 1.3, 0.87, 0.67, 0.46, and 0.25 kiloyears, although the latter presents a very low level of significance in Huascarán.

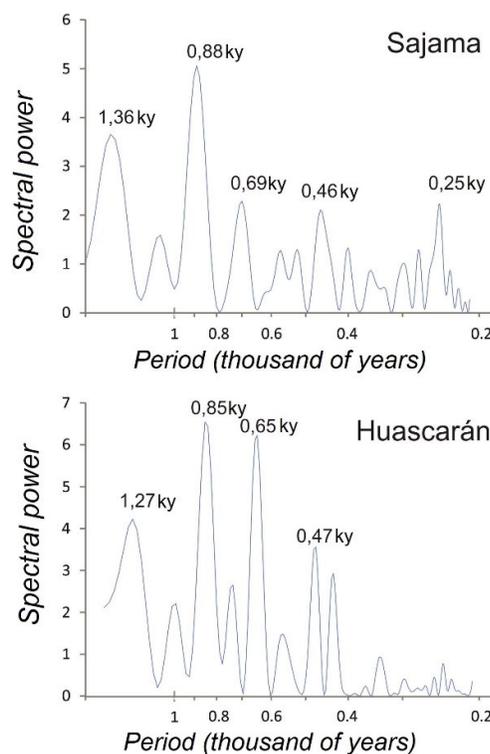


Figure 3. Spectral diagrams of the oxygen isotopes data series derived from Andean ice-cores. The more significant spectral peaks are indicated in thousands of years.

4. Discussion

On the one hand, the identification of essentially contemporaneous climate minima and maxima (within the margins of error) in the three ice-cores analyzed, and on the other, the significant coincidences in cyclicity revealed by the spectral analysis, highlight the supraregional nature of the climate changes during the late and middle Holocene period.

To discuss the possible origin of these climate changes, the Andean records were compared with well-contrasted climate forcing and climate patterns time series. Specifically, with the total solar irradiance series [25] and with the relative activity series of the thermohaline circulation in the North Atlantic (records of glacioderived deposits in the North Atlantic, [26]).

Furthermore, glacial deposits derived from the North Atlantic show the existence of five maxima, all of which correspond well with the Andean climatic minima identified in this study (Figure 4). The glacial deposits in the North Atlantic are direct evidences of the thermohaline circulation. The thermohaline, also named as Atlantic Meridional Overturning Circulation (AMOC), is a key climate forcing for its role on energy distribution between hemispheres [27,28].

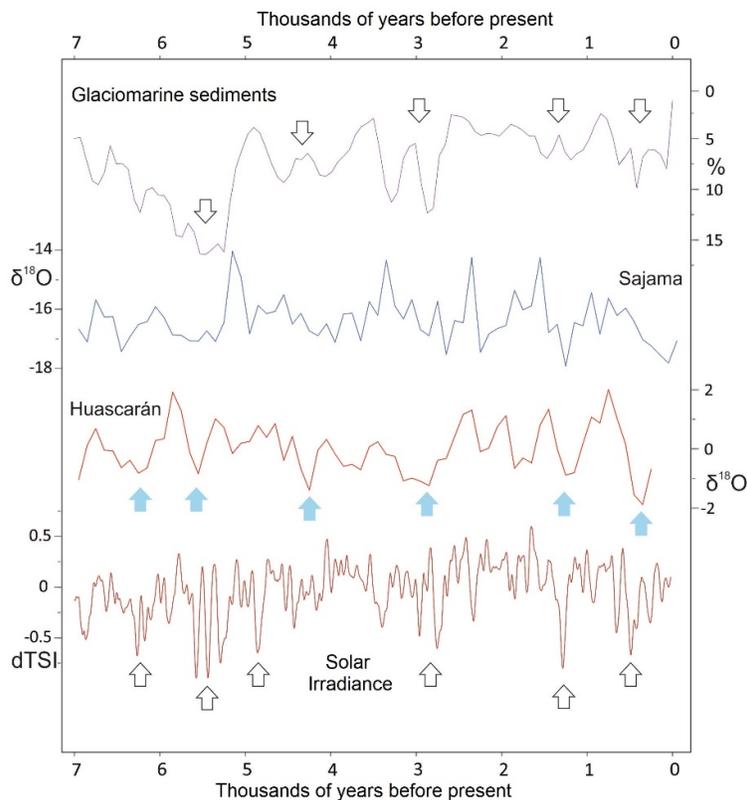


Figure 4. Comparison of the stable isotopes data series from Sajama and Huascarán Ice-Cores with glacioderivated deposits of the Northern Atlantic (values expressed in porcentaje of hematite grains; arrows indicated maximums corresponding to Iceberg massive entrances in the Atlantic, Bond et al. [26]), and with sun activity reconstruction (arrows indicating big solar minima; Steinhilber et al. [25]).

The AMOC velocity is very related to the meltwater flux that is naturally introduced in the North Atlantic area through Iceberg calving and terrain runoff [29]. These processes occur in cyclic “pulses” known as Heinrich Events, if the temporal scale ranges between 7 – 10 ky., or Dansgaard – Oeschger or Bond Cycles if it occurs each 1.5 ky. While Dansgaard-Oeschger events are related to the Pleistocene period, Bond Cycles are often referred to the Holocene [30]. Changes in the velocity (or a possible shut-off) can modify the interhemispheric energy balance, responding with global temperature variations in a short-term.

Slowing periods in the AMOC are closely related to rapid climate changes of abrupt cooling detected for the North Atlantic, but also for some other interconnected regions [28].

As tropical Atlantic Sea Surface Temperatures influence the large-scale atmospheric circulation, tropical eastern Pacific climate could be linked to AMOC [31]. Thermohaline circulation weakening is also a modulator of the Pacific El Niño pattern [32], which is also directly related to the Central Andes present temperatures [33] and Holocene palaeotemperatures [34].

The previous mentioned Bond cycles have been revealed present in different records sampled worldwide, showing possible Holocene climate teleconnection with North Atlantic. Renland Ice Cap core record (East central Greenland coast) showed climate variabilities in $\delta^{18}\text{O}$ levels that were matched to a millennial-scale cycle in line with Bond Cycles [35].

Zielhofer et al. [36] found a noticeable lack of winter rain in the western Mediterranean during Early Holocene through $\delta^{18}\text{O}$ records in Lake Sidi Ali (Morocco). The rain minima were coincident with Bond events while the opposite situation was found for the Late Holocene.

Records of the western European loess cores in Nussloch (Germany) matched also the variability of the North Atlantic, as they showed millennial scale changes in precipitation. This variability was pointed to connections with Bond Cycles [37].

In a local scale it is also possible to watch some coincidences between the Episodes here analyzed and other research. Some of the identified episodes, such as the Cold Episode V, matches cold conditions as marked by Weng et al. [38] in palynological analysis. This palynology also shows dry conditions coincident with the warm Episode IV during 5.0 Ky BP.

The above mentioned research in Nussloch [37] also identified a 4.2 ky potential anomaly that could match the Cold Episode IV (4.0–3.9 ka) registered in the Central Andes Ice-cores here revisited.

The cold Episode IV matches perfectly, as well, with glacier advances in the same study area. Cordillera Blanca could stand glacier readvances at 4 ky BP while the Nevado Sajama may have advances around the 4.4 ky BP [13]. The advances support the cold Episode IV, as some other episodes could be missing in the glacier record after geomorphological eroding of longest advances or during Little Ice Age.

Dry conditions [39] and a lack of glacier readvances are also coincident with a halt in climate variability between ~ 1.5 ky BP Cold Episode II and the warm Episode I during 0.4–0.7 Ky BP. Cold Episode I is coincident with the regional Little Ice Age so described for the Central Andes, and the researched glacier advances [40,41].

In parallel, the cycles recognized in the spectral analysis could be interpreted as connected to the global climate cycles related to these forcings. Specifically, the cycles defined by the longest periods (around 1.3 ky.) are close to the average length of Bond cycles, 1.5 ky. based on the recurrence of glacioderived deposits in the Atlantic and associated with changes in thermohaline circulation.

Links between North Atlantic Bond cycles and Aegean Sea climate fluctuations (eastern Mediterranean) were also pointed through Spectral Analysis conducted over Ti/Al and Zr/Si records of a sediment core [42]. Among others, this research found a 1,200 year periodicity, closely related to the variability here found for the Central Andes.

Some authors have questioned the actual existence of Bond Cycles, identifying the origin of climate changes in several coinciding causes rather than just in the melt water origin [43]. As melt water pulses could be the key triggering factor for the abrupt changes in the Early Holocene, some other changes for the Late Holocene could be caused by a combination of mechanisms such as volcanic patterns, orbital insolation or Sun activity [44–46].

In this research, shorter-period cycles, of 0.69 and 0.25 ky, could tentatively be correlated with solar activity cycles of comparable duration [47,48].

Comparison of $\delta^{18}\text{O}$ records from ice cores with forcing factor records (Figure 4) suggests a strong influence of solar activity on the three Central Andes ice cores. The major solar minima that mark the studied interval generally correspond well with episodes of minimum temperatures in the Central Andes.

Solar irradiation is the main driver for climatic circulation on Earth [25] and the paleoclimatic influence of solar activity has been widely proven [49,50].

Tropical Andes have been found to be very sensitive to even small changes in solar radiative forcing. Reduced solar activity in the Andes led to Little Ice Age period with a temperature decline of $-3.2 \pm 1.4^\circ\text{C}$ at least for the venezuelan Andes [51,52]. Unfortunately, still there is a lack of information in the lower temporal scale to indicate the solar influence on past temperatures, as records are not accurate or have enough resolution [53].

In the Laguna Comercocha of the peruvian Andes, changes in sun activity have been linked to precipitation patterns through the modification of the South American Summer Monsoon intensity [54]. Therefore, directly because of a lack of radiative energy or indirectly because of climate patterns

modification, solar forcing could be a key factor for the middle and late Holocene variability as revealed in the three reviewed ice-cores.

From all these findings, it can be deduced that the combined (and possibly interconnected) influence of solar activity and thermohaline circulation exert a strong control on climatic variations in the Southern Hemisphere and, in particular, to the Central Andes.

5. Conclusions

The main cold and warm episodes in the climate evolution of the central Andes over the last seven millennia have been identified using available data from glacial ice cores conducted in the area over the past few decades. The resolution achieved in this study is unprecedented in the Holocene palaeoclimatology of the region.

Spectral analysis techniques have shown to be a powerful tool for understanding the relationship between climate forcings and palaeoclimatic variables.

As many other regions, Late and Middle Holocene variability of the Central Andes could be related to not only one single forcing but to more than one direct or indirect causes. A reviewing of stable isotopes from Ice-cores records from Nevado Sajama (Bolivia), Nevado Illimani (Bolivia) and Nevado Huascarán (Peru), could detect periodicities of 1,300 years in the palaeotemperatures. Also, shorter common cycles have been identified for 0.87, 0.69, 0.46 and 0.25 ky.

The longest periodicity identified, the 1.3 ky, suggests Bond Cycles events could be influencing palaeotemperatures in the Central Andes, while shorter cycles such as 0.69 and 0.25 ky. could be matched to solar activity.

Correlation analysis conducted over the ice records have also shown the relationship between minimum temperature episodes and minimum in sun activity. Also, warm and cold episodes have been identified as contemporary to close areas such other Andean regions, or to the Central Andes itself.

Among others, the climate variability is interpreted as related to major changes in solar activity during the Holocene, as well as long-term variations in thermohaline circulation (Bond cycles).

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Abbreviations

The following abbreviations are used in this manuscript:

ITCZ	Inter Tropical Convergence Zone
ENSO	El Niño Southern Oscillation
N.	Nevado
BP	Before Present
Ky	Kiloyear (one thousand years)

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