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The history of the El Niño – Southern Oscillation according to lacustrine and marine sediments

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Resum

El gran impacte que El Niño — Oscil·lació del Sud (ENSO) té en la nostra societat industrialitzada ha esperonat la comunitat científica d'arreu a entendre quins són els mecanismes físics que el controlen, així com clarificar quina ha estat la seva història. El registre sedimentari de sensors naturals, com els llacs o la mar, ha permès reconstruir la història de l'ENSO. En aquest article, els autors donen una visió sintètica de la història d'aquest fenomen climàtic al llarg dels darrers quatre milions d'anys.

Paraules clau: El Niño – Oscil·lació del Sud (ENSO), història climàtica recent de la Terra, reconstruccions paleoclimàtiques, estudis multiparamètrics de sediments lacustres i marins.

Abstract

The large impact of the El Niño – Southern Oscillation (ENSO) in our industrial society has spurred the scientific community to understand the physical processes that trigger this climate phenomenum and to elucidate its history. The sedimentary record of natural sensors, such as lakes and seas, was used to reconstruct the history of the ENSO and to obtain a comprehensive history of this climate phenomenon throughout the last 4 million years.

Keywords: El Niño – Southern Oscillation (ENSO), recent climate history of the Earth, paleoclimate reconstructions, multi-proxy lacustrine and marine sediment studies

Extreme climate phenomena have major effects on the socio-economic structure of our advanced technological society. The sudden increase in mortality that occurred in France (and to a lesser extent in Spain) as a consequence of the anomalous meteorological conditions (temperatures 2–6 °C higher and precipitation 25–50 mm lower than average) during the summer of 2003 is a good example of these effects. Another example is the considerable economic loss endured during the extremely hot summer of 1983 along much of the Mediterranean coast of the Iberian Peninsula (increase in forest fires and water shortages).

The current warming trend of the global mean temperature (0.6° ± 0.2 C in the last 140 years), attributed to anthropic activities, especially the exponential use of fossil fuels, is generally considered to be the main cause of the increased frequency and intensity of these extreme climatic phenomena [1]. Hence, forecasting their frequency and intensity is of paramount importance in order to prevent and mitigate their consequences. At present, forecasting is performed using meteorological series for computer modelling (atmospheric pressure, precipitation, temperature, etc.).

Although considerable advances have been made in our understanding of the climatic evolution of the Earth during the last 150 years, by studying the available instrumental meteorological series, extreme climatic events have been less well documented. The lack of documentation can be attributed to the limited time span covered by these series. The meteorological series usually cover the last 60 years and only few of them span the whole 20th century. This short period does not allow us to perform reliable forecasting of these extreme climatic events, marking them as "unusual" or "extraordinary". One example of this limitation is the extreme climatic phenomena with a recurrence pattern of about 40 years. These phenomena are present in the instrumental series only once or twice. Hence, there is an urgent need for extending meteorological series back in time in order to accurately forecast extreme climatic phenomena.

One way to extend instrumental meteorological series back in time is to use a "natural sensor" such as oceans, lakes, tree rings, and cave stalagmites. These biological and geological

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records are very sensitive to climate change, and they allow us to observe changes at a very high temporal resolution (even at a seasonal scale, in the case of laminated lake or marine sediments and tree rings) over long time periods (i.e., the last 15,000 years). These "natural sensors" are in dynamic equilibrium with the main environmental conditions, and when these conditions change the sensors react by adapting to them in order to achieve new equilibrium conditions. For example, an increase (decrease) in precipitation leads to a rise (drop) in the lake water level, which in turn, induces changes in the physico-chemical conditions of the lake. These new physico-chemical conditions give rise to variations in the ecological structure of limnic organisms (appearance/disappearance of new/old species) and to chemical precipitation of new minerals (i.e., carbonates and salts), among other changes.

All these changes are reflected in the sediments that settle at the bottom of the aquatic ecosystems. Hence, the characterization of these sediments reveals the paleoclimatic evolution of the studied area, while studies of the geological and biological records provide insight into the main mechanisms that triggered the paleoclimatic evolution (i.e. solar activity, North Atlantic Oscillation (NAO), El Niño – Southern Oscillation [ENSO]) and to establish the recurrence periods of extreme climatic phenomena.

The present-day ENSO phenomenon

One of the extreme climatic phenomena that have attracted the attention of both the general public and the scientific community is the El Niño – Southern Oscillation (ENSO). This is mainly due to the impact that El Niño has on the global socio-economic structure. For example, in 1997, there were catastrophic floods along the coasts of Perú, Ecuador, and along most of the east coast of the USA. At the same time, there were devastating droughts in the Peruvian and Bolivian altiplano, northeast Brazil, Indonesia, New Guinea, and Australia. Owing to extreme dry conditions, widespread forest fires raged in most of Kalimatan (New Guinea). The intense smoke from these extensive fires disrupted air traffic and caused the temporary closure of the airports in Singapore, Malaysia, and Indonesia. The beginning of 1998 was marked by devastating floods that affected western Canada, Southeast Asia, and southern Africa, while the summer of that year was abnormally cold and rainy in southeast Asia.

The ENSO not only triggers catastrophes. In 1998, the rainfall increased by more than 500% in the hyper-arid regions of Ecuador, giving rise to exuberant vegetation cover for the following three years. The local communities adapted themselves to this precipitation regime and took advantage of these short

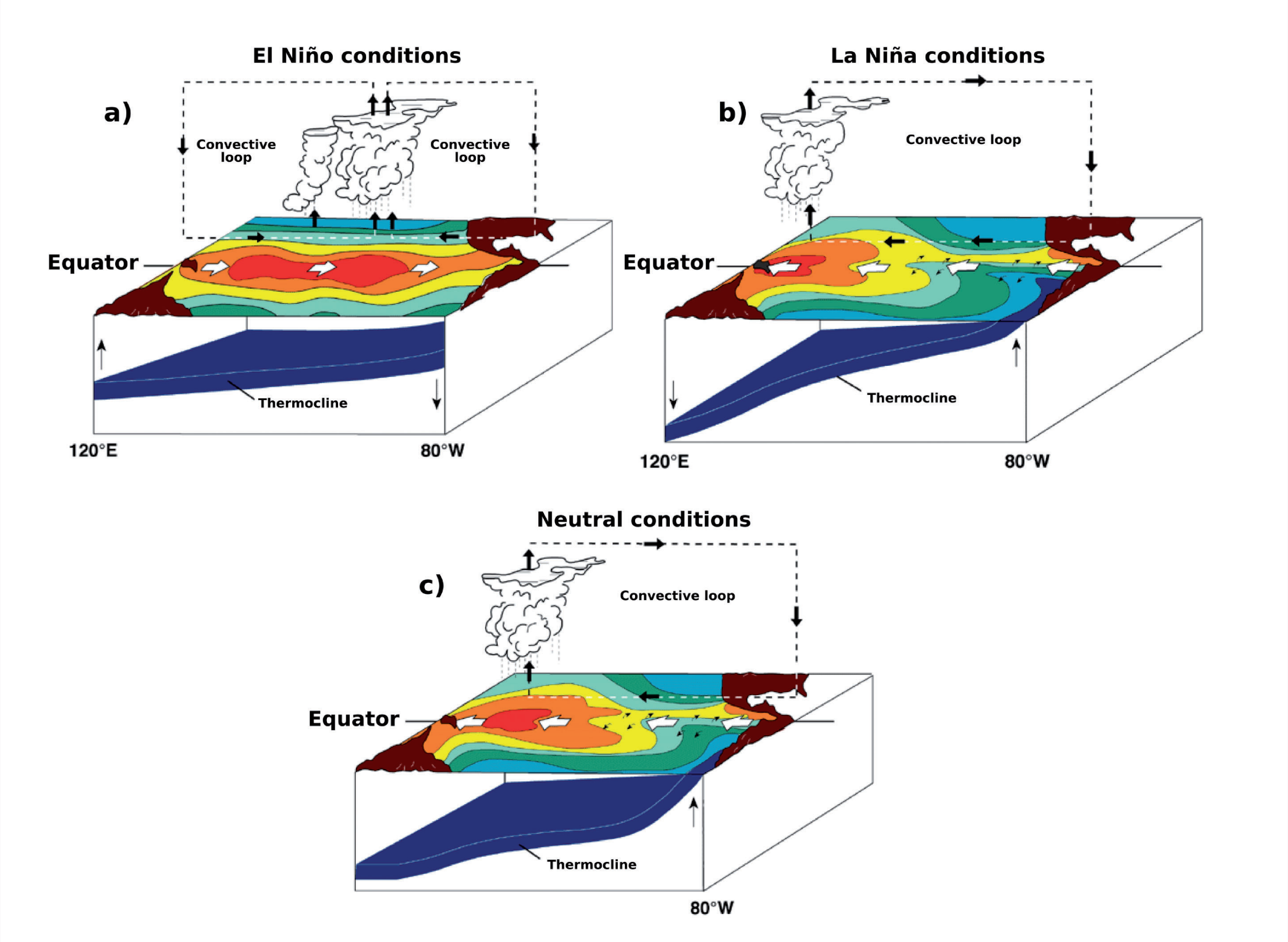

Figure 1. Atmospheric circulation and location of the thermocline during (**a**) El Niño and (**b**) La Niña events, and (**c**) neutral conditions. Modified from: http://www.pmel.noaa.gov/tao/elnino/nino-home.html.

rainy periods to develop an intensive agriculture [2]. The ENSO phenomenon is the most prominent year-to-year climate variation on Earth [3].

Physical mechanisms of the ENSO

The name El Niño was coined by the fishermen of Perú. The western coast of South America is one of the most productive fishing areas in the world, due to the upwelling of cold and nutrient-rich Antarctic waters caused by the easterly winds (Fig.1a). This upwelling is attributed to the position of the thermocline in the surficial waters (<100 m deep) in this area. The upwelling of these cold and nutrient-rich waters favors high biological productivity, which is expressed, among other parameters, by considerable anchovy shoals and large colonies of marine birds along the Pacific coast of South America. From time to time (approximately between 2 and 7 years), around Christmas, the high biological productivity is interrupted by the influx of warm water masses from the eastern tropical latitudes of the Pacific Ocean. The sea surface temperature (SST) undergoes a sharp increase in temperature such that the warm water masses push the thermocline downwards, diminishing (or even blocking completely) the upwelling of nutrient-rich waters and thus sharply reducing biological activity [4] (Fig. 1a). The predominant winds during these warmings are the westerlies. The coincidence of this decrease in biological activity with Christmas led the fishermen to name the phenomenon "El Niño" ("El Niño Jesús" or the Christ child). Subsequent studies have shown that El Niño has a counterpart, known as "La Niña". Thus, El Niño represents the warm phase and La Niña the cold episodes (Fig. 1b).

El Niño is part of a more complex atmospheric phenomenon known as the Southern Oscillation, giving rise to the complete name of this climatic phenomenon, the El Niño – Southern Oscillation (ENSO). The ENSO has been defined as a dipole or oscillator; while a number of mechanisms have been proposed, none of them have been fully accepted to date [4–6]. The dipole concept does not imply the idea of cyclicity since every ENSO event varies in duration, magnitude, temporal evolution, and spatial structure [3].

Under normal or "neutral" conditions, there is a SST warming in the western tropical area of the Pacific Ocean, northwards of Australia and eastwards of Indonesia. Simultaneously, at these latitudes but close to the coasts of Perú and Ecuador, the water temperature is 4 – 10°C colder, mainly due to the upwelling of the cold Antarctic waters. This water temperature gradient triggers the atmospheric pressure gradient, which in turn controls the trade winds (Fig. 1c). Periodically, for reasons that remain largely unexplained, warm surficial waters expand eastwards. The influx of warm waters triggers the sink of the thermocline, a reduction of the SST gradient, and therefore to a decrease in the atmospheric pressure gradient, with subsequent weakening of the trade winds. The chain of warming events in the equatorial Pacific gives rise to the El Niño phenomenon described in the previous paragraph (Fig. 1a). The opposite situation arises when cold waters from the Antarctic spread westwards, strengthening the trade winds and enhancing the upwelling. These are the La Niña climate events (Fig. 1b).

The ENSO phenomena give rise to modifications in the ocean water currents and in the atmospheric circulation. The index that defines the ENSO is the SST anomaly of the area, which ranges between 90° W – 150° W and 5° S – 5° N (Fig. 2). This geographical area is known as El Niño 3.4. Positive SST anomalies are identified as El Niño events, whereas negative SST anomalies correspond to La Niña events. These anomalies must be one standard deviation higher than the mean neutral

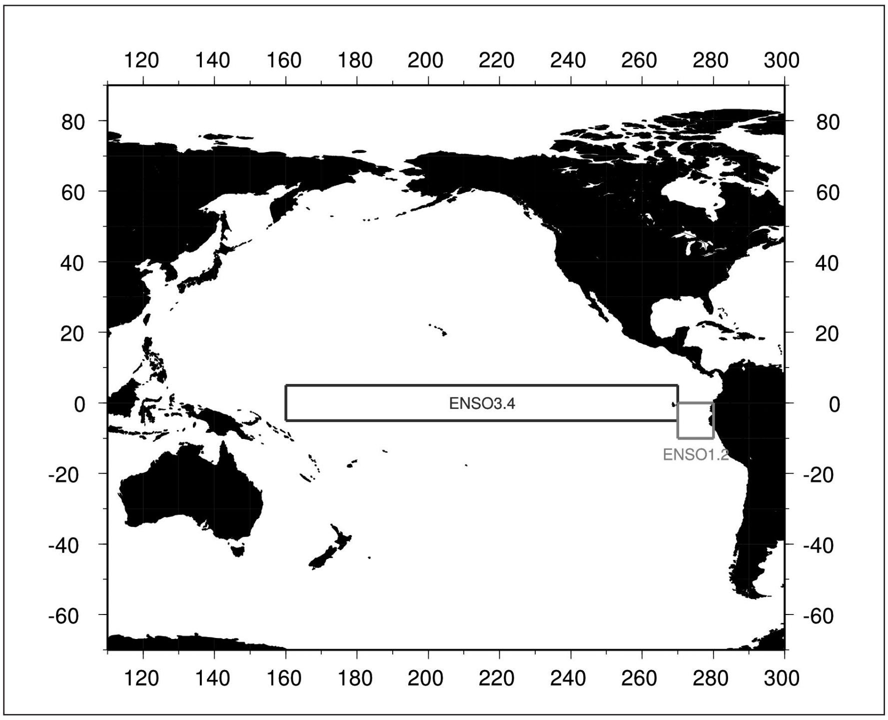

Figure 2. Map of the tropical Pacific Ocean. The two rectangles mark the location of the El Niño 3.4 and El Niño 1.2 definition areas. The former ranges between 90ºW – 150ºW and 5ºS – 5ºN and the latter between 80ºW – 90ºW and 10ºS – 0ºS.

conditions for a period exceeding 5 months to be considered as El Niño or La Niña events [7]. Furthermore, not all ENSO events have the same evolution and affect the same geographical areas. For example, some ENSO events affect the eastern coast of the USA, others impact the South American coast, and a few (only the strongest ones) have catastrophic effects in both areas. The first early warning announcements forecasting ENSO conditions several months in advance appeared in the weekly reports of the National Oceanic and Atmospheric Agency (NOAA) of the USA. However, the predictions only took into account the El Niño 3.4 area, which mainly affects the USA and not the coast of South America. These announcements resulted in considerable confusion in South American countries, such as Ecuador and Chile, until the situation was resolved by defining a second ENSO area. The latter is known as "El Niño 1.2" and is located between 80° W – 90° W and 10° S – 0° S (Fig. 2). The atmospheric changes due to the El Niño dynamics are defined by an index known as the Southern Oscillation Index (SOI), which is the normalized difference in the sea-level atmospheric pressure between Darwin (Australia) and Tahití. Negative anomalies indicate El Niño conditions, positive ones La Niña conditions. A comparison of the SST and SOI indices demonstrated that they record the same climatic process (Fig. 3).

Characterization of the instrumental meteorological series has shown that the intensity and recurrence patterns of the ENSO have not been constant over time. The 1920s and 1960s were marked by large and frequent ENSO events, whereas in the 1930s few such events occurred. The instrumental meteorological series of the Iberian Peninsula have shown that the ENSO signal only appears from the 1960s onwards [8].

The ENSO phenomenon has been used in many global climate models (GCM) to forecast its behavior in emission scenarios in which the present CO_2 concentration is doubled. These models have produced contradictory results. Some authors have claimed that, from the 1970s onwards, the ENSO has increased in frequency and duration [9] as a result of global warming and that this tendency will continue. Other authors have argued that this recent behavior does not deviate from that expected for natural climate variability [3].

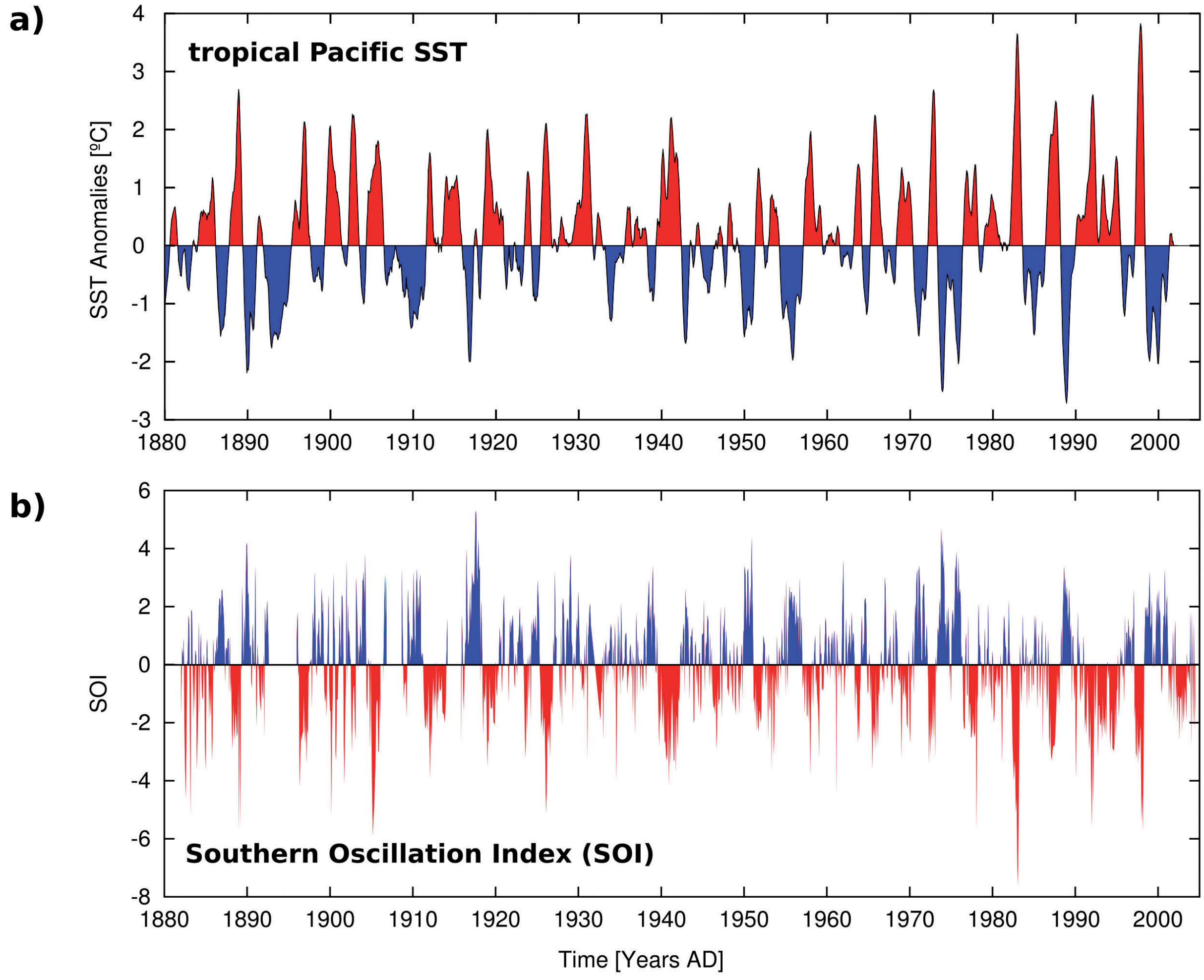

Figure 3. Two indexes of the ENSO phenomena. (**a**) Pacific Ocean sea surface temperature (SST) anomalies of the zone ranging between 90ºW – 150ºW and 5ºS – 5ºN. Positive values (in red) indicate El Niño conditions whereas negative ones (in blue) depict La Niña conditions. (**b**) Normalized difference of the sea-level atmospheric pressure between Darwin (Australia) and Tahití. This index defines the Southern Oscillation Index (SOI). Positive values (in blue) indicate La Niña conditions and negative ones (in red) El Niño conditions.

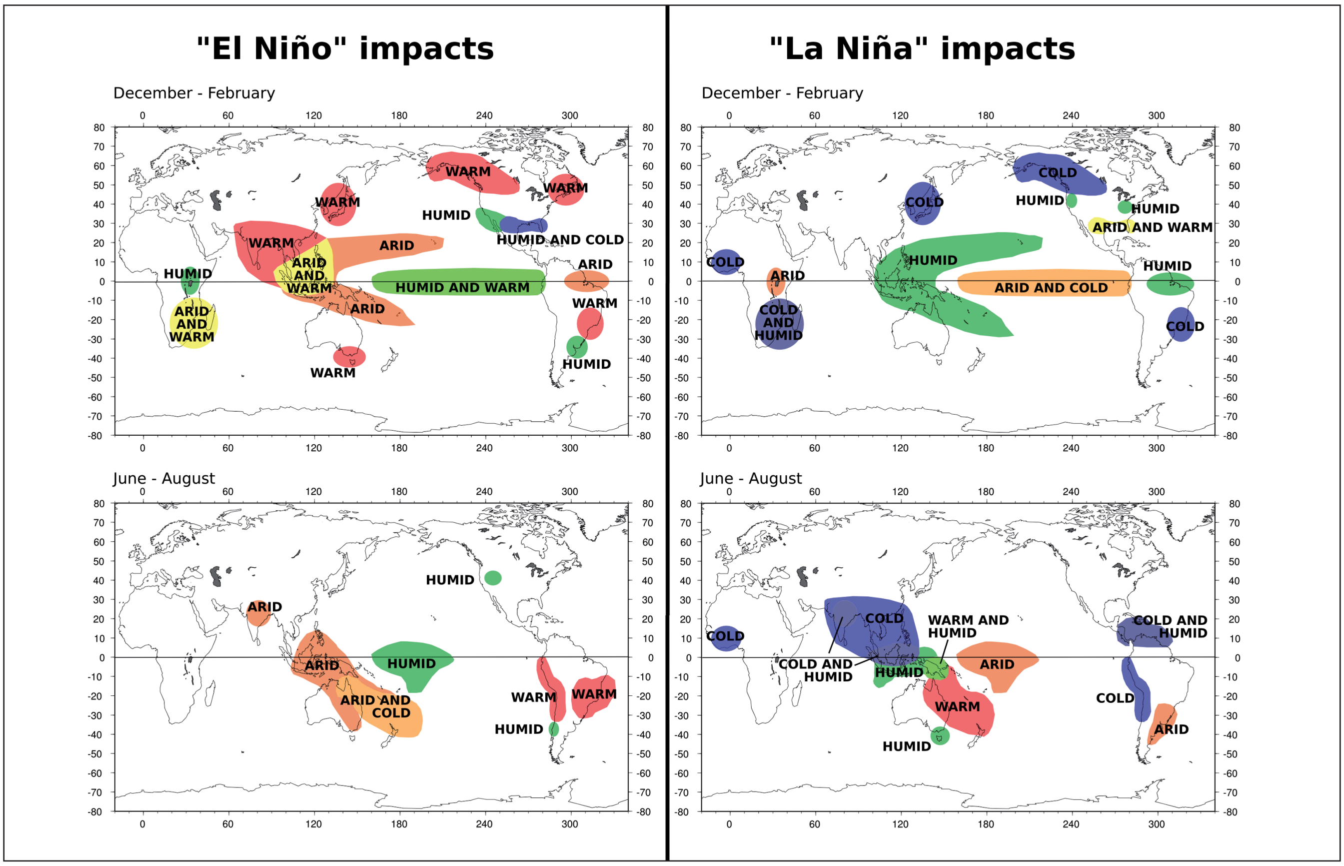

Figure 4. Worldwide distribution and impact of the El Niño (left) and La Niña (right) events during winter (up) and summer (bottom). Modified from: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm_impacts.shtml

Clearly, despite significant advances in our understanding of the ENSO, a number of questions remain unanswered:

- What are the main mechanisms that trigger the ENSO phenomenon? Is it a stochastic climatic phenomenon as some authors claim? Or is it related to solar activity? And if so, is this relationship straight or non-linear?
- What are the spatio-temporal patterns of this climatic phenomenon? When did it start? Has its behavior been constant through time, or have there been periods when it has not been active?
- What will the future behavior of the ENSO be like under global warming scenarios? Will it increase in its frequency and/or intensity? Will only the El Niño events increase and not those of La Niña? Will the ENSO influence the same geographical areas or will it spread towards other areas?

The sedimentary records from lacustrine and marine ecosystems can provide answers to some of these questions.

The history of the ENSO as recorded in lacustrine and marine sediments

The onset of the ENSO during the Miocene and Pliocene (last 4 Myr)

There is no solid evidence for the onset of the ENSO phenomena. Some studies have proposed that the closure of the Isthmus of Panamá, between 3.5 and 4.0 million years (Myr), gave rise to the onset of the present-day ENSO [10]. Closure enhanced heat transport in the Atlantic Ocean, with subsequent modifications of the water current. More recently, it has been proposed that closure of the Indonesian Seaway had a greater effect on heat transport (and, hence, on the onset of the ENSO) than the closure of the Isthmus of Panama [12]. Still other researchers have attributed the ENSO cyclicity to a much earlier period (54–33 Myr), namely the Eocene Green River Formation [13].

Moreover, there is no consensus on the temporal evolution of the ENSO phenomena over time. Some marine sedimentary records indicate that the ENSO was a permanent phenomenon during the Pliocene, between 5 and 3 Myr, when conditions were much warmer than today [13]. These records also mark the end of the warm climate conditions and of the permanent El Niño for two reasons:

- Growth of the northern continental glaciers at the start of the Quaternary (approx. 2.8 Myr ago) because of an amplification of the obliquity of the Earth
- The presence of cold surface waters in oceanic upwelling zones at low latitudes (both coastal and equatorial)

The Pliocene lacustrine sequence of Villarroya (Sierra de Cameros, northern Spain) is one of the oldest continental records containing signals with the same periodicities as the ENSO [14]. The sedimentary record consists of alternating light and dark thin layers and laminae. Each pair of light and dark laminae is called a varve, which represents the sediment deposited within a year. The light laminae are made up of gastropods, ostracods, and charophytes, reflecting the productivity cycle of late summer and autumn. Their varying thickness has been attributed to changes in the temperature (i.e., thicker light laminae would imply higher productivity, and hence, higher summer temperatures) [14]. This sedimentary record was dated by magnetostratigraphy at approximately 2.8 Myr [15]. Spectral analysis of these varves suggests that sedimentation was driven by solar activity, ENSO-like phenomena, the North Atlantic Oscillation (NAO), and Quasi-Biennial Oscillation (QBO). This lacustrine record shows that the ENSO phenomena had the same climate dynamics as they do today.

The Late Quaternary (last 1 Myr)

The cyclical transgressive shelf successions of the Middle Pleistocene Ichijiku and Kakinokidai Formations (ca. 700,000 years) in the Boso Peninsula (Japan) provided evidence that these successions were formed approximately every 10 years, mainly due to periodic strengthening of the ENSO and to the reduced frequency of typhoons in the Western Pacific [16]. The ENSO triggered fluctuations in the paths and speeds of the paleo-Kuroshio oceanographic current (the strongest surface current in the Western Pacific region, derived from the North Equatorial Current), which controlled the main climatic oscillations in the Western Pacific. This sedimentary succession allowed us to identify short, high-frequency oscillations in the ENSO intensity, similar to those observed in the present-day instrumental series.

A previously described ENSO model [17] clearly showed that the ENSO only ceased twice during the last 500,000 years: during the Younger Dryas [the last cold spell before the present-day interglacial conditions; dated between 10,000 and 11,000 years before present(BP)], and at about 400,000 years ago, when the climatic conditions were similar to those of the Younger Dryas [18].

The last Glacial cycle (last 130,000 years)

There are very few continuous records that cover the last 130,000 years and enable us to characterize the ENSO evolution at millennial and centennial time scales, and most of them correspond to marine sequences [19–21]. Nevertheless, a few continental records allow us to accurately describe inter-decadal changes in ENSO frequency and intensity during short time windows of the last glacial stadial [16, 22–24].

The oxygen isotope record of these marine sequences reflects changes in precipitation and in the temperature regimes at centennial and millennial time scales. Heavier δ^{18}O values indicate more arid and/or cold conditions and vice versa. Spectral analyses carried out on δ^{18}O records obtained from corals indicate that during the last glacial stadial there were no major changes in ENSO frequency or regularity [20]. Only millennial-scale shifts were observed. Stott and coworkers claimed that the El Niño conditions correlate with stadials at high latitudes, whereas La Niña conditions correlate with interstadials [25].

Continental lacustrine sequences revealed that the ENSO intensity increased during the glacial period and involved geographical areas other than those presently affected, because of the global atmospheric circulation differed. The landslide-dammed lakes of northwestern Argentina (formed between 40,000 and 25,000 years BP) together with other evidence [26, 27] indicate that the climate conditions in tropical and subtropical South America during the glacial period were wetter than at present [22, 23]. The sediments of the lakes that developed behind the landslides are made up of varves, the thickness of which reflects changes in rainfall (thick varves correspond to humid years and vice versa). Spectral analyses of varve thickness provided evidence for ENSO-like cyclicities (Fig. 5). Thicker varves seemed to be associated with enhanced ENSO events, and thus heavy rainfall.

The Last Glacial Maximum (LGM) corresponds to the coldest temperatures attained during the last glacial stadial and is dated between 25,000 and 21,000 years BP. During the LGM, the temperature pattern in the tropical Pacific resembled that of El Niño, with reduced zonal and meridional low-latitude gradi-

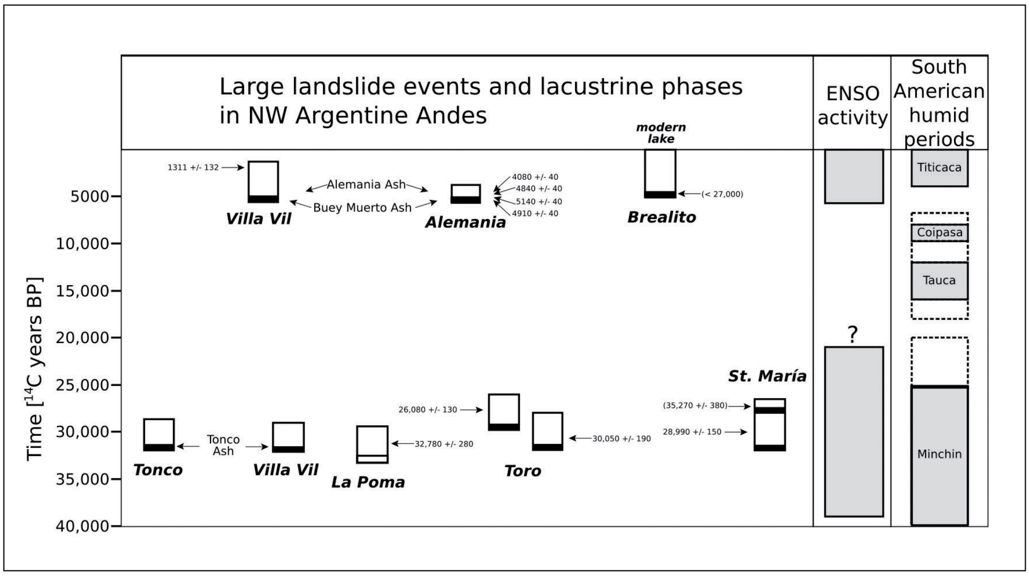

Figure 5. Correlation of landslide and lacustrine events in northwestern Argentina with tropical South American wet episodes. Black horizontal bars depict landslide events; lacustrine phases are denoted by gray rectangles. Modified from [23].

ents [21]. At about 20,000 years BP, a warm period triggered an increase in seasonality, favoring an increase in the number of El Niño events. The abrupt warming phase, dated at approximately 14,800 years BP, induced a sharp increase of ~2°C of the zonal gradient and a shift towards more La Niña-like conditions [21]. It seems that this shift was not global. The sedimentary record of Lynch's Crater, located in northeast Australia, suggests that between 17,900 and 12,500 years BP the frequency and amplitude of El Niño-like conditions in this area were greater [25]. The enhanced ENSO expanded the regional aridity, resulting in greater disruption of the vegetal cover.

The last 10,000 years

The increase in the zonal gradient, initiated at about 14,800 years BP, was blocked during the Younger Dryas. This induced a progressive decrease in seasonality, which, in turn, triggered the progressive weakening and a reduction in the amplitude of the ENSO [28, 29]. The establishment of a long-term La Niña pattern in the tropical Pacific during this period seems to have been a consequence of the ENSO reduction [21]. Hence, the onset of the Holocene (the present-day interglacial conditions which began about 10,000 years BP) was marked by the absence of the ENSO phenomena, especially of the El Niño pattern. Spectral analyses of the gray-scale curve of the annually laminated sediments of Laguna Pallcacocha (Ecuador) showed that the ENSO bands (particularly the El Niño bands, since the rainfall in this area is triggered by this climate phenomenon) were absent from ~15,000 to 7,000 years BP (Fig. 6) [28, 29]. This absence was most likely due to a reduced zonal SST gradient caused by: (a) elevated SSTs in the equatorial and coastal upwelling zones of the eastern Pacific Ocean, (b) a smaller and less intense western Pacific warm pool, or (c) by elevated SSTs and smaller Pacific warm pools. Apparently, the oscillation between La Niña and El Niño states was muted [30]. A comprehensive coupled GCM confirmed the weak amplitude of the ENSO cycle between 9,000 and 6,000 years BP [31]. A possible explanation for the absence of the ENSO in the early/middle Holocene can be found in the orbital configuration of the Earth at that time [32]. The progressive reduction of seasonality also triggered the gradual weakening of the summer monsoon in East Asia and the growing strength of the summer monsoon in the Indian Ocean (the two most important monsoon systems at

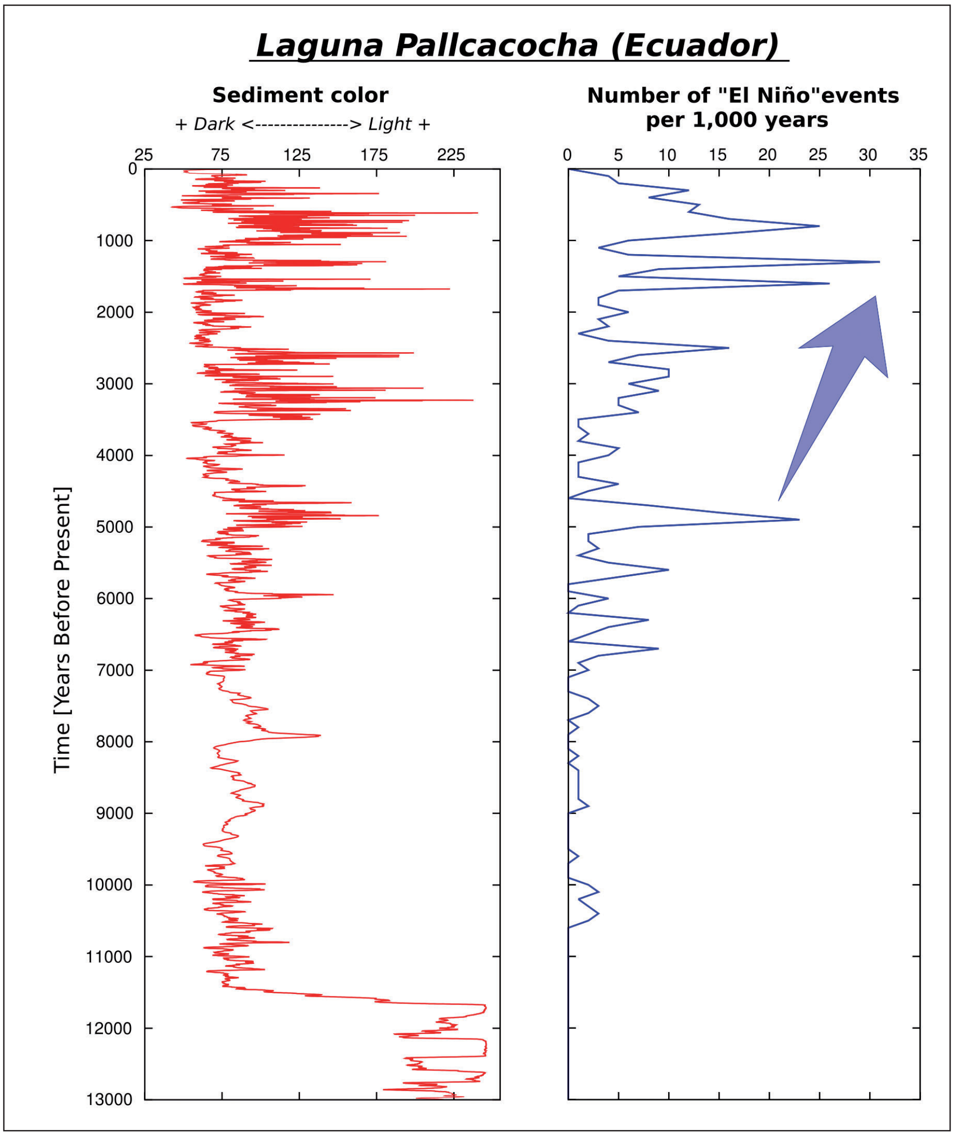

Figure 6. Color variation curve for sediments from Laguna Pallcacocha (Ecuador). El Niño events trigger catastrophic rainfall episodes in the catchment of the lake. These erode the non-consolidated sediments of the catchment, transporting and depositing them within the lake. The massive sediment inputs are reflected in the sediments by light color laminae and indicate El Niño events (left). The number of light laminae per 1,000 years allows the number of El Niño events to be calculated. The blue arrow shows the intensification of El Niño events from 5,000 to almost the present (right). Modified from [28].

lower latitudes), thereby changing the rainfall patterns in East Asia [33].

According to some researchers, the onset of the present-day ENSO conditions occurred about 7,000 years BP [28, 29, 34]. However, others have claimed that this climatic phenomena started about 5,000 years ago [33, 35]. The ENSO frequency did not increase monotonically but in a gradual pulsative way [29]. The processes that modified the ENSO status are poorly constrained and controversial, although changes in the mean thermocline state of the eastern equatorial Pacific [34] and long-term orbital changes [29] have been proposed.

The intensity of the ENSO grew from ~5,000 to ~3,000 years BP, when it reached its highest values [35]. Terrestrial and marine records located within the Indo-Pacific Warm Pool (IPWP) showed that the reconstructed El Niño temperature perturbations were larger than any observed in the modern record [36]. It should be pointed out that changes in the temperature, size, and positioning of the IPWP (an area defined between 10ºN and 20ºS and between 90ºE and 180ºE) profoundly affect global climate and, hence, ENSO development. The temperature perturbations were reconstructed using the Sr/Ca and U/Ca ratios measured in corals as paleothermometers (warmer waters imply greater incorporation of Sr and U in the coral carbonates, and higher values of the Sr/Ca and U/Ca ratios). Tighter coupling in the Pacific Ocean between the Inter-Tropical Convergence Zone, located further to the south than at present, and the Southern Oscillation could have served to amplify the variability in precipitation associated with the ENSO [35]. The highest ENSO values coincide with the onset of humid conditions in South America.

The last 1,000 years

Large ENSO frequencies and amplitudes, exceeding those that occurred in the 20th century, have characterized the last 1,000 years [17]. The $\delta^{18}O$ isotope record from the island of Palmyra (tropical Pacific) suggests that the ENSO events of the 17th century were as severe as those caused by the 1997 El Niño event (Fig. 7). These large oscillations in frequency and amplitude were not observed during the 12th to 15th centuries. The foregoing results are in good agreement with lacustrine records, such as those of Lago Puyehue (Argentina) [38]. The varved sedimentary record of this lake shows that the enhanced El Niño events coincided with thin varves (El Niño events imply arid conditions in this region). Furthermore, the ENSO behavior was not the same worldwide. Tree rings from subtropical North America reveal that the 17th and 18th centuries, coinciding with the Little Ice Age, were characterized by low-amplitude ENSO events [39]. The mechanisms that control this ENSO decadal-scale variability are not known. It has been proposed that this variability is associated with changes in the mean state as a result of natural decadal-scale variability or greenhouse warming [40, 41]. The following hypotheses have been suggested to account for the ENSO decadal-scale variability:

- Noise in the climate system, most probably of atmospheric origin, interfering with the ENSO onset [42, 43]
- An inverse relationship with solar activity [39, 44] (high solar activity would imply less ENSO variability and vice versa) via the thermostat mechanism [45]
- Changes in the SST of the Tropical Atlantic [46]

Conclusions

Lacustrine and marine sedimentary records have proved to be valuable archives of the probable onset and evolution of the ENSO.

Apparently, the onset of the ENSO conditions occurred at about 3.5–4 Myr, as a result of the closure of either the Isthmus of Panama or the Indonesian Seaway. These climate phenomena have been constant through time, except during the Younger Dryas (10,000–11,000 years BP) and at about 400,000 years BP, when climatic conditions were similar to those of the Younger Dryas. Geological records have highlighted the absence of the ENSO bands during these two periods.

No evidence for any major change in the ENSO frequency or regularity during the last glacial stadial (the last 130,000 years BP) has been found. Lacustrine sequences have revealed only increases in the intensity of the ENSO events during this time period. The increase in seasonality that occurred at ca. 20,000 years BP intensified the El Niño events whereas the marked increase in the zonal gradient at ca. 15,000 years BP favored La Niña-like conditions.

The abrupt Younger Dryas cold-spell led to a decrease in seasonality, resulting in ENSO weakening and amplitude re-

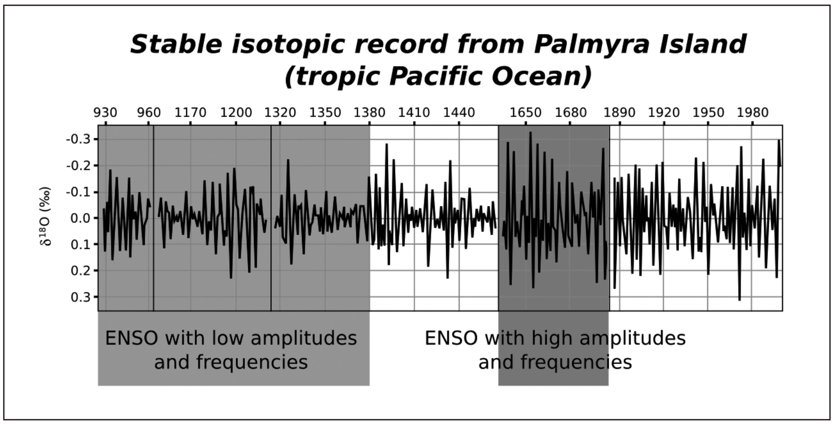

Figure 7. ENSO variability was isolated by applying a high bandpass filter (2–7 years) to the deseasoned monthly coral $\delta^{18}O$ anomaly data from Palmyra Island (tropical Pacific). Frecuency and intensity of the ENSO events are expressed by the oscillations of the curve. Modified from [37].

duction. The beginning of the Holocene was marked by the absence of the ENSO. Present-day ENSO conditions started between ca. 7,000 and 5,000 years BP. ENSO intensity attained its highest values at about 3,000 years BP.

The last 1,000 years have been characterized by ENSO frequencies and amplitudes that exceeded those of the 20th century. The amplitude was smaller for the period between the 12th and 14th centuries whereas the 17th century was marked by severe ENSO events.

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References

[1] Inter-Governmental Panel on Climate Change (IPCC) (2001), Climate Change 2001: Synthesis Report, Cambridge University Press.

[2] Holmgren, M.; Scheffer, M. (2001), El Niño as a window of opportunity for the restoration of degraded arid ecosystems, Ecosystems, 4, 151–159.

[3] McPhaden, M.; Zebiak, S.; Glantz, M. (2006), ENSO as an integrating concept in Earth science, Science, 314, 1740–1745.

[4] Chavez, F.; Strutton, P.; Friederich, G.; Feely, R.; Feldman, G.; Foley, D.; McPhaden, M. (1999), Biological and chemical response of the equatorial Pacific Ocean to the 1997-98 El Niño, Science, 286, 2126–2131.

[5] Chen, D.; Cane, M.; Kaplan, A.; Zebiak, S.; Huang, D. (2004), Predictability of El Niño over the past 148 years, Nature, 428, 733–736.

[6] Kessler, W. (2002), Is ENSO a cycle or a series of events?, Geophysical Research Letters, 29, 2125.

[7] Trenberth, K. (1997), The definition of El Niño, Bulletin of American Meteorological Society, 78, 2771–2777.

[8] Rodó, X.; Baert, E.; Comín, F. (1997), Variations in rainfall in Southern Europe during the present century: relationships between the North Atlantic Oscillation and the El Niño – Southern Oscillation, Climate Dynamics, 13, 275–284.

[9] Fedorov, A.; Philander, S. (2000), Is El Niño changing?, Science, 288, 1997–2002.

[10] Roof, S.; Mullins, H.; Gartner, S.; Huang, T.; Joyce, E.; J., P. (1991), Climatic forcing of cyclic carbonate sedimentation during the last 5.4 million years along the West Florida continental margin, Journal of Sedimentary Petrology, 61, 1070–1088.

[11] Cane, M.; Molnar, P. (2001), Closing of the Indonesian Seaway as a precursor to East African aridification around 3-4 million years ago, Nature, 411, 157–162.

[12] Ripepe, M.; Roberts, L.; Fischer, A. (1991), ENSO and sunspot cycles in varved Eocene oil shales from image analysis, Journal of Sedimentary Petrology, 61, 1155–1163.

[13] Fedorov, A.; Dekens, P.; McCarthy, M.; Ravelo, A.; deMenocal, P.; Barreiro, M.; Pacanowski, R.; Philander, S. (2006), The Pliocene Paradox (Mechanisms for a permanent El Niño), Science, 312, 1485–1489.

[14] Muñoz, A.; Ojeda, J.; Sánchez-Valverde (2002), Sunspot-like and ENSO/NAO-like prediodicities in lacustrine laminated sediments of the Pliocene Villarroya Basin (La Rioja, Spain), Journal of Paleolimnology, 27, 453–463.

[15] Pueyo-Morer, E.; Muñoz, A.; Parés, J. (1996), Magnetoestratigrafía preliminar de los materiales pliocenos de la cubeta de Villarroya (Sierra de Cameros, La Rioja), Geogaceta, 20, 1029–1032.

[16] Horikawa, K.; Ito, M. (2004), Long-term ENSO-like events represented in the Middle Pleistocene shelf successions, Boso Peninsula, Japan, Palaeogeography, Palaeoclimatology, Palaeoecology, 203, 239–251.

[17] Clement, A.; Cane, M.; Seager, R. (2001), An orbitally driven tropical source for abrupt climate change, Journal of Climate, 14, 2369–2375.

[18] Cane, M. (2005), The evolution of El Niño, past and future, Earth and Planetary Science Letters, 230, 227–240.

[19] Hughen, K.; Schrag, D.; Jacobsen, S.; Hantoro, W. (1999), El Niño during the last interglacial period recorded by a fossil coral from Indonesia, Geophysical Research Letters, 26, 3129–3132.

[20] Tudhope, A.; Chilcott, C.; McCulloch, M.; Cook, E.; Chappell, J.; Ellam, R.; Lea, D.; Lough, J.; Shimmield, G. (2001), Variability in the El Niño-Southern Oscillation through a glacial-interglacial cycle, Science, 291, 1511–1517.

[21] Koutavas, A.; Lynch-Stieglitz, J.; Marchitto, T.; Sachs, J. (2002), El Niño-like pattern in ice age tropical Pacific Sea Surface Temperature, Science, 297, 226–230.

[22] Trauth, M.; Strecker, M. (1999), Formation of landslide-dammed lakes during a wet period between 40,000 and 25,000 yr B.P. in northwestern Argentina, Palaeogeography, Palaeoclimatology, Palaeoecology, 153, 277–287.

[23] Trauth, M.; Bookhagen, B.; Marwan, N.; Strecker, M. (2003), Multiple landslide clusters record Quaternary climate changes in the northwestern Argentine Andes, Palaeogeography, Palaeoclimatology, Palaeoecology, 194, 109–121.

[24] Turney, C.; Kershaw, A.; James, S.; Branch, N.; Cowley, J.; Fifield, L.; Jacobsen, G.; Moss, P. (2006), Geochemical changes recorded in Lynch’s Crater, Northeastern Australia, over the past 50 ka, Palaeogeography, Palaeoclimatology, Palaeoecology, 233, 187–203.

[25] Stott, L.; Poulsen, C.; S., L.; Thunell, R. (2002), Super ENSO and global climate oscillations at millennial time scales, Science, 297, 222–226.

[26] Godfrey, L.; Lowenstein, T.; Li, J.; Luo, S.; Ku, T.-L.; Alonso, R.; Jordan, T. (1997), Registro continuo del Pleistoceno tardío basado en un testigo de halita del Salar de Hombre Muerto, Argentina, VIII Congreso Geológico de Chile, 1, 332–336.

[27] Turcq, B.; Pressinotti, M.; Martin, L. (1997), Paleohydrology and paleoclimate of the past 33,000 years at the Tamaduá river, central Brazil, Quaternary Research, 47, 284–294.

[28] Rodbell, D.; Seltzer, G.; Anderson, D.; Abbott, M.; Enfield, D.; Newman, J. (1999), An 15,000-year record of El Niño-driven alluviation in southwestern Ecuador, Science, 283, 516–520.

[29] Moy, C.; Seltzer, G.; Seltzer, D.; Anderson, D. (2002), Variability of El Niño/Southern Oscillation activity at millennial time scales during the Holocene epoch, Nature, 420, 162–165.

[30] Sandweiss, D.; Richardson III, J.; Reitz, E.; Rollins, H.; Maasch, K. (1996), Geoarchaeological evidence from Perú for a 5000 years B.P. Onset of El Niño, Science, 273, 1531–1533.

[31] Otto-Bleisner, B.; Brady, E.; Shin, S.; Liu, Z.; Shields, C. (2003), Modeling El Niño and its tropical teleconnections during the last glacial-interglacial cycle, Geophysical Research Letters, 30, 2198.

[32] Clement, A.; Seager, R.; Cane, M. (2000), Supression of El Niño during the mid-Holocene by changes in the earth’s orbit, Paleoceanography, 15, 731–737.

[33] Hong, Y.; Hong, B.; Lin, Q.; Shibata, Y.; Hirota, M.; Zhu, Y.; Leng, X.; Wang, H.; Yi, L. (2005), Inverse phase oscillations between the East Asian and Indian Ocean summer monsoons during the last 12000 years and paleo-El Niño, Earth and Planetary Science Letters, 231, 337–346.

[34] Loubere, P.; Richaud, M.; Liu, Z.; Mekik, F. (2003), Oceanic conditions in the eastern equatorial Pacific during the onset of ENSO in the Holocene, Quaternary Research, 60, 142–148.

[35] Gagan, M.; Hendy, E.; Haberle, S.; Hantoro, W. (2004), Post-glacial evolution of the Indo-Pacific Warm Pool and El Niño-Southern Oscillation, Quaternary International, 118-119, 127–143.

[36] Corrège, T.; Delcroix, T.; Recy, J.; Beck, W.; Cabioch, G.; Le Cornec, F. (2000), Evidence for stronger El Niño-Southern Oscillation (ENSO) events in a mid-Holocene massive coral, Paleoceanography, 14, 465–470.

[37] Cobb, K.; Charles, C.; Cheng, H.; Edwards, L. (2003), El Niño/Southern Oscillation and tropical Pacific climate during the last millennium, Nature, 424, 271–276.

[38] Boës, X.; Fagel, N. (2008), Relationships between southern Chilean varved lake sediments, precipitation and ENSO for the last 600 years, Journal of Paleolimnology, 39, 237-252.

[39] D’Arrigo, R.; Cook, E.; Wilson, R.; Allan, R.; Mann, M. (2005), On the variability of ENSO over the past six centuries, Geophysical Research Letters, 32.

[40] Fedorov, A.; Philander, S. (2001), A stability analysis of tropical ocean-atmosphere interactions: Bridging measurements and theory for El Niño, Journal of Climate, 14, 3086–3101.

[41] Trenberth, K.; Hoar, T. (1996), The 1990-1995 El Niño-Southern Oscillation event: Longest on record, Geophysical Research Letters, 23, 57–60.

[42] Graham, N.; White, W. (1988), The El Niño cycle: a natural oscillator of the Pacific ocean-atmosphere system, Science, 240, 1293–1302.

[43] Kleeman, R.; Power, S. (1994), Limits to predictability in a coupled ocean-atmosphere model due to atmospheric noise, Tellus A, 46, 529–540.

[44] Kirov, B.; Georgieva, K. (2002), Long-term variations and interrelations of ENSO, NAO and solar activity, Physics and Chemistry of the Earth, 27, 441–448.

[45] Clement, A.; Seager, R.; Cane, M.; Zebiak, S. (1996), An ocean dynamical thermostat, Journal of Climate, 9, 2190–2196.

[46] Ariztegui, D.; Bösch, P.; Davaud, E. (2007), Dominant ENSO frequencies during the Little Ice Age in northern Patagonia: the varved record of proglacial Lago Frías, Argentina, Quaternary International, 161, 46–55.

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