A rainy northern Atacama Desert during the last interglacial

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[1] The response of the northern extension of the Atacama Desert and the Peruvian upwelling system to climate conditions during the Last Interglacial ([LIG]; ~125kyr ago) was tracked using molecular fossils of marine and terrestrial organisms preserved in Peruvian shelf sediments. High resolution records of ODP Site 1229 (past 145 kyr) indicated that warmer and wetter conditions (rainfall and river runoff) along the coast occurred during the LIG, when global temperatures were comparable or even higher than today. A ~3°C warming of surface waters, enhanced water column stratification, rainfall and river runoff were associated with low primary productivity and a ~1.5°C decrease in the temperature gradient across the Equatorial Pacific (i.e., weak Walker circulation), suggesting a prolonged El Niño-like response of the tropical Pacific during the LIG. In contrast, the late Holocene ([LH] last 3 kyr) was characterized by colder surface waters, higher export and primary productivity, and a drier climate. **Citation:** Contreras, S., C. B. Lange, S. Pantoja, G. Lavik, D. Rincón-Martínez, and M. M. Kuypers (2010), A rainy northern Atacama Desert during the last interglacial, *Geophys. Res. Lett.*, *37*, L23612, doi:10.1029/2010GL045728.

1. Introduction

[2] The west coast of South America is characterized by a narrow arid and continuous belt that is virtually devoid of vegetation and extends over more than 3,000 km from northern Peru (5°S) to northern Chile (30°S) [*Rundel et al.*, 1991]. The hyperarid core (annual precipitation <3mm yr^{-1}) known as the Atacama Desert, is located between 15°S and 30°S. Permanent cold coastal conditions prevent precipitation by developing and enhancing atmospheric stability in the coastal region as a result of the strong atmospheric subsidence of the Subtropical Pacific Anticyclone (SPA) that drives upwelling forced by southeasterly trade winds channelled along the Andes, and the northward-flowing cold Humboldt Current [*Hartley et al.*, 2005; *Rech et al.*, 2006].

[3] At present, the southeasterly trade winds are part of the east-west atmospheric circulation (Walker cell). The strength of the trade winds and Walker circulation are mostly controlled by the equatorial sea surface temperature (SST) gradient between the cold surface waters of the eastern Pacific and the western Equatorial Pacific warm pool. During modern-day El Niño (EN) events, when warm waters spread across the Pacific and along the Peruvian shelf and SST is particularly high, trade winds and upwelling weaken, atmospheric stability breaks, and positive rainfall anomalies occur along the northern extension of the Atacama Desert [*Philander*, 1990]. Such rainfall episodes (i.e., 1982–1983 and 1997–1998) substantially stimulate a profuse growth of vegetation in a normally barren landscape, and increase river discharge [*Holmgren et al.*, 2006].

[4] Ice core and marine proxy records of the last 800 kyr indicate that the LIG (~125 kyr ago) was characterized by temperatures as warm as or even warmer than at present. Whether the LIG represents a likely scenario for the future, given current global warming, is uncertain. Nevertheless, potential climate and oceanographic responses to a rising in global temperatures may be evaluated by comparison to the LIG [*Kukla et al.*, 2002].

[5] We used molecular fossils (i.e., biomarkers) of marine and terrestrial organisms preserved in organic rich shelf sediments of the highly productive Peruvian coastal upwelling region (Ocean Drilling Program (ODP) Site 1229; 10.98°S, 77.95°W (Figure 1)) to reconstruct environmental changes during the LIG and compare them to the LH. Our study provides evidence of enhanced rainfall over the northern extension of the Atacama Desert during the LIG associated with a warming of coastal waters and a reduction of zonal SST gradients in the Equatorial Pacific, contrary to the LH which appears to be a dry period linked to enhanced upwelling.

2. Data and Methods

[6] We studied the upper 12 meters (past 145 ka) of ODP Site 1229 (151m water depth), a revisit of ODP Site 681. Total organic carbon (TOC) was determined with a Carlo Erba NA-1500 elemental analyzer. Lipids were analyzed and quantified by GC and GC-MS (Trace GC-MS; Thermo Finnigan). Diatoms from discrete sediment samples were identified and counted on permanent microscope slides. Methodological details can be found in the auxiliary material.[1]

[7] Our stratigraphic framework was established by correlating the magnetic susceptibility record from Site 1229E with Site 681B (Figure S1). The scarce abundance and patchy down core distribution of benthic foraminifera limited the establishment of an age model based on foraminiferal oxygen isotope stratigraphy. Thus, we adopted the published age model of Site 681 based on the occurrence of unique diatom assemblages and oxygen isotope correlations [*Schrader*, 1992]. The age model (Table S1) was refined by radiocarbon dating of the bulk organic fraction of the upper Holocene section [*Skilbeck and Fink*, 2006]. Tuning of our alkenone-based SST record to the one of Site TR163-19

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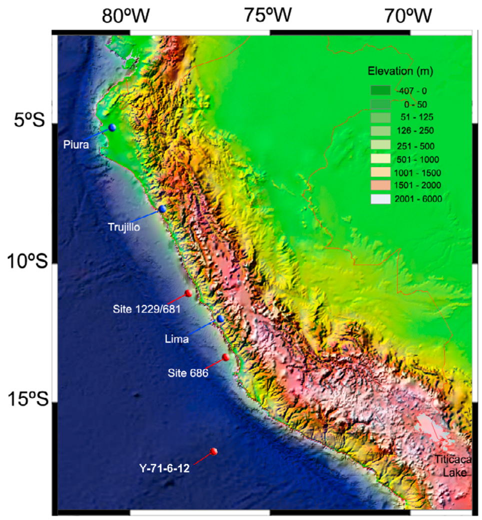

Figure 1. Map showing the location of ODP Site 1229 (re-drilling of Site 681) and South American topography. The location of Site 686 (13.48°S; 76.89°W [446m]), where *Brodie and Kemp* [1994] found evidence for enhanced river input during the last interglacial (LIG), is also indicated. Site Y71-6-12 (16.44°S; 77.56°W; [2734m] [*Loubere et al.*, 2003a]) mentioned in the text is also included.

(2.27°N; 90.95°W) [*Lea et al.*, 2006] supports the allocation of the LIG (Figure S2). Given the limitations of the sedimentary record at Site 1229, our discussion focuses only on a comparison of the LIG to the LH, two time intervals separated by more than 100,000 years, and for which we have a reliable age control (see Text S1).

3. Results and Discussion

[8] The record contains a well-preserved LH section (upper 2.3 m) consisting of clay-rich diatomateous ooze with some depositional unconformities around 2.5 m and 3.5 m (Site 1229 [*Shipboard Scientific Party*, 2003]). These unconformities are common on the Peruvian continental shelf around the last glacial/Holocene transition and have been attributed to variations in sea level and upwelling strength [*Skilbeck and Fink*, 2006; *Makou et al.*, 2010]. The LIG is characterized by low sedimentation rates (on average 10 cm kyr^{-1}); while elevated sedimentation rates (70–100 cm kyr^{-1}) were found at the LH [*Skilbeck and Fink*, 2006]. These apparent elevated sedimentation rates are most probably related to enhanced sediment focusing (i.e., syndepositional sediment redistribution by bottom currents) due to increased upwelling strength in the area during the LH (see discussion in Text S1).

[9] We used the alkenone unsaturation index to reconstruct past SST [*Prahl et al.*, 1988]. The transition from MIS 6 to 5 was associated with a ~3°C warming reaching a maximum of 24.5°C during the LIG with SSTs ~2°C warmer than the LH values (Figure 2a). A sharp cooling marked the end of the LIG. The mean SST value of the LH of 21.8°C is closer to the modern-day summer average SST value of 23°C than to the winter average value of 18°C (http://podaac.jpl.nasa.gov/). Warm conditions along the eastern tropical Pacific have been previously reported for the LIG [*Lea et al.*, 2006], and a 2°C warming from MIS 6 to MIS 5 was recorded farther south of our study area, at ~17°S [*Prahl et al.*, 2006].

[10] The presence of warm surface waters along the Peruvian coast increases stability in the water column, enhances stratification, and thus, reduces nutrient supply, primary productivity, and ultimately TOC flux to the sediment [*Chavez et al.*, 1999]. Overall TOC content varied from 2 to 8% (Figure 2b) with lower TOC values (~3.5%) during MIS 5 than in the LH (>5%, albeit high variability). These results were interpreted as higher LH export productivity (TOC flux) than during the LIG. Because differential extents of carbon preservation, or sediment focusing may affect TOC contents at Site 1229, we also compare the TOC record with published paleo-productivity estimates based on marine planktonic diatoms and benthic foraminifer assemblages (Figure 2g) [*Schrader*, 1992; *Loubere et al.*, 2003a]. These diatom and foraminifer records reveal that the nutrient supply to the eastern Pacific and subsequent primary productivity was substantially diminished during the LIG (Figure 2g).

[11] Potential changes in the species composition of the marine plankton were tracked using specific molecular fossils (Table S2). High abundances of the lipids 1,14 C_{28} alkyl diol and 12-hydroxy methyl alkanoates, biomarkers of *Proboscia* diatoms [*Sinninghe Damsté et al.*, 2003], indicate that *Proboscia* diatoms were a major constituent of the community during the LIG interval (Figure 2c). Both lipid biomarkers (diols) have been originally proposed as indicators for high-nutrient conditions in the monsoonal upwelling of the Arabian Sea]. In the highly productive Peru and northern Chile upwelling systems, the diatom genus *Chaetoceros* (considered an upwelling indicator) dominates the phytoplankton community while *Proboscia* diatoms increase in abundance during post-upwelling, when the water column is more stratified [*Tarazona et al.*, 2003; *Herrera and Escribano*, 2006]. Thus, we propose that high abundance of *Proboscia* biomarkers and the high correlation (r = 0.61; n = 49) with SSTs (Table S2) is indicative of enhanced water column stratification over the Peruvian shelf during the LIG (see Text S3).

[12] Although caution is advised when interpreting the TOC normalized biomarker abundances (see further discussion in Text S4) due to the elevated TOC values and sedimentation rates over the LH, non-normalized *Proboscia* biomarker abundances does not show the same trend and at no other time reach the high levels of the LIG (Figure S3c). Late Holocene accumulation rates of *Proboscia* biomarkers (e.g., 1,14 C_{28} alkyl diol) were similar to LIG accumulation rates when considering the 10 times higher sedimentation rates and elevated TOC during LH compared with LIG (see Text S4). We attribute the high LH accumulation mostly to the elevated sedimentation associated to syndepositional sediment redistribution due to enhanced upwelling strength and export productivity instead of higher water column stratification as is the case for the LIG. Our interpretation is in accordance with *López-Otálvaro et al.* [2008] who used calcareous nannofossil assemblages at ODP Site 1240 (Panama Basin), and suggested a deepening of the nutri-thermocline and a collapse of the upwelling system of the eastern Pacific during the MIS 5e and typically intense eutrophic conditions during the Holocene.

[13] A sudden occurrence of freshwater diatoms (Figure 2d) at the LIG onset, and a major rise in terrestrial plant biomarker abundance during the LIG suggest freshwater input by river

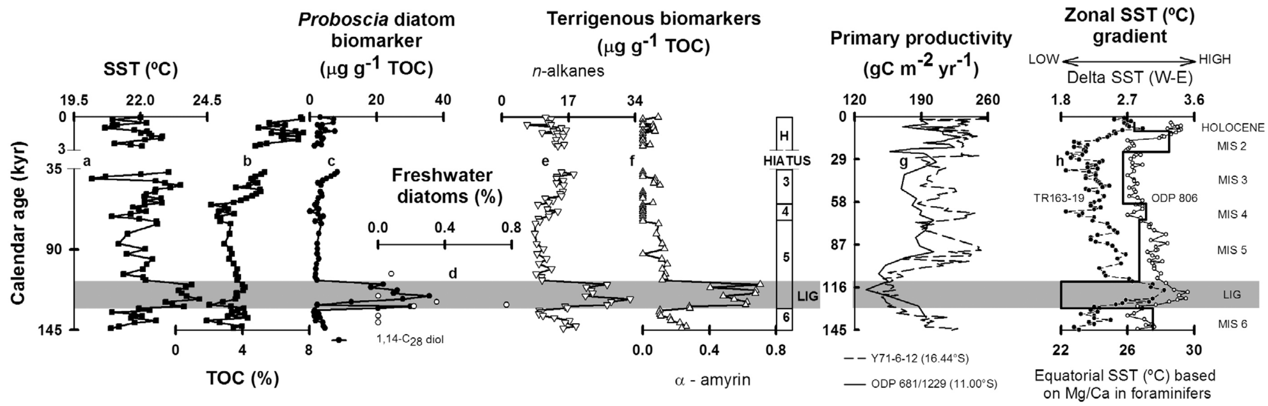

Figure 2. Downcore records of geochemical data from Ocean Drilling Program (ODP) Site 1229E (this study) compared to primary productivity estimates reported for the Peruvian upwelling system and the zonal sea-surface temperature gradient across the equatorial Pacific for the past 145 kyr. (a) Reconstructed sea-surface temperature (SST °C) based on the alkenone unsaturation index, showing ~3°C warming during last interglacial (LIG). (b) Percent total organic carbon (TOC). (c) Concentration of 1,14 C_{28} alkyl diol, a biomarker for *Proboscia* diatoms [*Sinninghe Damsté et al.*, 2003]; increments in the *Proboscia* biomarker abundance indicates more stratified water column conditions during the LIG. Proxies of continental input attributed to rainfall/river runoff; note that they were enhanced during the LIG. (d) Relative abundance of freshwater diatoms, (e) sum of C_{25} to C_{35} *n*-alkanes concentrations mainly derived from leaf waxes, and (f) concentrations of α-amyrin derived from angiosperms. (g) Paleo-estimates of primary productivity (gC m^{-2} yr^{-1}) based on marine diatoms from ODP Site 681 (11°S; same location as ODP Site 1229) [*Schrader*, 1992], and benthic foraminifer assemblage distributions from core Y71-6-12 [*Loubere et al.*, 2003a]. Both records show the lowest primary productivity of the past 145 kyr during the LIG. (h) SST reconstructed by *Lea et al.* [2000] based on Mg/Ca data of planktic foraminifera in the western (Site 806B; 0.32°N 159.37°E [2520m]) and eastern (Site TR163-19; 2.27°N 90.95°W [2348m]) equatorial Pacific over the past 145 kyr. Superimposed is the zonal SST gradient across the equatorial Pacific (solid line) inferred from the difference in SST (Delta SST W-E) between the western and eastern equatorial Pacific. Delta SST was calculated by removing the colder eastern SST from the warmer western SST averages for MIS 6, MIS 5e (LIG), MIS 5 (excluding LIG), MIS 4, MIS 3, and MIS 2. The reduced thermal gradient across the equatorial Pacific can be interpreted as reduced trade winds and weakened Walker circulation during the LIG. Age boundaries were adopted from *Martinson et al.* [1987]. Even and odd numbers on the central panel denote warm interglacial (3 and 5) and glacial (4 and 6) marine isotope stages (MIS) and H indicates late Holocene ([LH] last 3 kyrs). The grey bar across the figure refers to the LIG. All molecular fossil concentrations (μg g^{-1}) were normalized by TOC (μg g^{-1} TOC).

runoff at Site 1229 (Figures 2e and 2f and Table S2). The total lipid fractions of the shelf sediments contain long-chain (C_{25} to C_{35}) *n*-alkanes and *n*-alcohols that are largely derived from leaf waxes of terrestrial plants [*Eglinton and Hamilton*, 1967], as well as α-amyrin and taraxerol, which are biomarkers for terrestrial angiosperms [*Killops and Frewin*, 1994]. The *n*-alkanes and *n*-alcohols can be introduced into the marine environment by both eolian and fluvial input, while α-amyrin and taraxerol are mainly transported by rivers and further redistributed by bottom currents [*Volkman et al.*, 1987]. We ascribe the enhanced abundance of terrestrial *n*-alkanes (Figure 2e), *n*-alcohols (Table S2), α-amyrin (Figure 2f), and taraxerol (Table S2) to riverine transport of terrestrial organic matter to Site 1229 as a direct consequence of increased rainfall over the northern extension of Atacama Desert during the LIG. These findings are in good agreement with the deposition of coarse and silt-rich sub-millimetre laminae at ODP Site 686 (Peru margin at 13.5°S (Figure 1)), whose occurrence was attributed to enhanced river runoff during MIS 5e [*Brodie and Kemp*, 1994].

[14] In contrast to the LIG setting, the LH is characterized by a lower α-amyrin average accumulation rate (11 μg m^{-2} kyr^{-1} compared to 25 μg m^{-2} kyr^{-1} in the LIG), a higher average accumulation rate of *n*-alkanes (9955 μg m^{-2} kyr^{-1} versus 1134 μg m^{-2} kyr^{-1} during the LIG), and the absence of taraxerol (see Text S4). These results, together with colder LH SSTs, imply long-term influence of cold coastal upwelling and drier conditions on land (Figure 2). Non-normalized terrestrial biomarker abundances (Figures S3e and S3f) also support the interpretation of wetter conditions and higher fluvial input during the LIG *versus* drier conditions for the LH, especially in view of the absence of taraxerol in LH sediments. We suggest a prevailing eolian source for terrigenous biomarkers during the LH and a primarily fluvial source during the LIG (further discussion in the auxiliary material).

[15] Data of Lea and co-workers [*Lea et al.*, 2000] were used to reconstruct the Pacific equatorial west-east thermal gradient during the past 145 kyr, subtracting the colder eastern SST from the warmer western SST (Figure 2h). In the modern climate system, this thermal gradient is closely linked to the strength of the trade winds and the Walker circulation [*Philander*, 1990]. Interestingly, the lowest thermal gradient (~1.8°C) corresponds to the LIG. We consider this as indicative of strongly reduced trade winds (weakened Walker circulation), and as a long-term EN-like setting during the LIG. Conversely, the Holocene was characterized by a higher thermal equatorial gradient (Figure 2h) suggestive of stronger

trade winds affecting ocean temperature and productivity. This is consistent with *Loubere et al.* [2003b] who suggested the enhancement of trade winds, cooling of surface and thermocline waters, and increased nutrient supply and productivity for the LH when compared with the middle Holocene. Recently, a high resolution sedimentary record at nearby ODP Site 1228 [*Makou et al.*, 2010] revealed strengthened upwelling and productivity with concomitant increases in the predominance of both warm (EN) and cold (LN) phases of the EN Southern Oscillation (SO) during the LH.

[16] Additional support of a long-term EN-like response of the tropical Pacific during the LIG comes from continental climate records (i.e., inland Colombia and the South American Altiplano), which exhibit prolonged dry conditions during modern-day EN years [*Garreaud and Aceituno*, 2001; *Poveda et al.*, 2006]. Warm and dry conditions in Colombia during the LIG were inferred from a pollen record of Lake Fuquene, Eastern Cordillera of Colombia [*van der Hammen and Hooghiemstra*, 2003]. Studies from Salar Uyuni, Lake Titicaca, and the Huiñaimarca sub-basin also revealed that the most extreme dry event over the last 150 kyr occurred during the LIG (i.e., 130 to 120 kyr) [i.e., *Hanselman et al.*, 2005; *Gosling et al.*, 2008]. Moreover, charcoal deposits in north-eastern Australia indicated drought periods around the LIG [*Kershaw et al.*, 2003]; enhanced droughts are also typical features of modern-day EN events in Australia [*Philander*, 1990].

[17] Although there are several indications that "short-term" (i.e., inter-annual to decadal-scale) ENSO variability apparently increased in the LH compared to the middle and early Holocene [i.e., *Sandweiss et al*., 2001; *Tudhope et al*., 2001], the long-term pattern seems to behave different. From a "climate-continuum-point-of-view" periods recognized as interglacials are warmer and very similar at glacial-interglacial timescales, especially when compared to the colder glacial periods [i.e., *Rincón-Martínez et al*., 2010]. This apparent similarity is a definition based on the global mean temperature of the earth. However, regionally we might expect considerable differences between interglacials. As shown here, we found two different regional oceanographic settings in the eastern Pacific resembling a long-term El Niño and La Niña during the LIG and the LH, respectively.

4. Conclusion

[18] We provide evidence of increased rainfall and river runoff over the northern extension of the Atacama Desert (Peru) during the LIG. The warm surface waters, enhanced water column stratification, lower primary productivity and wetter conditions of the LIG were probably associated with a long-term response (EN-like) of the tropical Pacific mean state. In contrast, cold coastal upwelling, higher export and primary productivity together with drier conditions on land suggest a different ocean-atmosphere dynamics for the last 3 kyr. Similar oceanographic and climate responses to present day conditions seem to be the result of short-term (centennial-scale) changes in ENSO activity driven by tropical insolation. The more EN-like tropical Pacific conditions of the LIG may not only have contributed to the globally warmer climate during this time interval but may also serve as an analogue for the consequences of ongoing and future global warming.

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References

Brodie, I., and A. E. S. Kemp (1994), Variations in biogenic and detrital fluxes and formation of laminae in late Quaternary sediments from the Peruvian coastal upwelling zone, *Mar. Geol.*, *116*, 385–398, doi:10.1016/0025-3227(94)90053-1.

Chavez, F. P., et al. (1999), Biological and chemical response of the equatorial Pacific Ocean to the 1997–98 El Niño, *Science*, *286*, 2126–2131, doi:10.1126/science.286.5447.2126.

Eglinton, G., and R. J. Hamilton (1967), Leaf epicuticular waxes, *Science*, *156*, 1322–1335, doi:10.1126/science.156.3780.1322.

Garreaud, R., and P. Aceituno (2001), Interannual rainfall variability over the South American Altiplano, *J. Clim.*, *14*, 2779–2789, doi:10.1175/1520-0442(2001)014<2779:IRVOTS>2.0.CO;2.

Gosling, W. D., M. B. Bush, J. A. Hanselman, and A. Chepstow-Lusty (2008), Glacial-interglacial changes in moisture balance and the impact on vegetation in the southern hemisphere tropical Andes (Bolivia/Peru), *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *259*, 35–50, doi:10.1016/j.palaeo.2007.02.050.

Hanselman, J., W. D. Gosling, and G. M. Paduano (2005), Contrasting pollen histories of MIS 5e and the Holocene from Lake Titicaca (Bolivia/Peru), *J. Quat. Sci.*, *20*, 663–670, doi:10.1002/jqs.979.

Hartley, A. J., G. Chong, J. Houston, and A. E. Mather (2005), 150 million years of climatic stability: Evidence from the Atacama Desert, northern Chile, *J. Geol. Soc.*, *162*, 421–424, doi:10.1144/0016-764904-071.

Herrera, L., and R. Escribano (2006), Factors structuring the phytoplankton community in the upwelling site off El Loa River in northern Chile, *J. Mar. Syst.*, *61*, 13–38, doi:10.1016/j.jmarsys.2005.11.010.

Holmgren, M., et al. (2006), Extreme climatic events shape arid and semi-arid ecosystems, *Front. Ecol. Environ*, *4*, 87–95, doi:10.1890/1540-9295(2006)004[0087:ECESAA]2.0.CO;2.

Kershaw, A. P., S. van der Kaars, and P. T. Moss (2003), Late Quaternary Milankovitch-scale climatic change and variability and its impact on monsoonal Australia, *Mar. Geol.*, *201*, 81–95, doi:10.1016/S0025-3227(03)00210-X.

Killops, S. D., and N. L. Frewin (1994), Triterpenoid diagenesis and cuticular preservation, *Org. Geochem.*, *21*(12), 1193–1209, doi:10.1016/0146-6380(94)90163-5.

Kukla, G. J., et al. (2002), Last interglacial climates: Quaternary research, *Quat. Res.*, *58*, 2–13, doi:10.1006/qres.2001.2316.

Lea, D. W., D. K. Pak, and H. J. Spero (2000), Climate impact of late Quaternary equatorial Pacific sea surface temperature variations, *Science*, *289*, 1719–1724, doi:10.1126/science.289.5485.1719.

Lea, D. W., et al. (2006), Paleoclimate history of Galápagos surface waters over the last 135,000 yr, *Quat. Sci. Rev.*, *25*, 1152–1167, doi:10.1016/j.quascirev.2005.11.010.

López-Otálvaro, G.-E., J.-A. Flores, F. J. Sierro, and I. Cacho (2008), Variations in coccolithophorid production in the Eastern Equatorial Pacific at ODP Site 1240 over the last seven glacial–interglacial cycles, *Mar. Micropaleontol.*, *69*, 52–69, doi:10.1016/j.marmicro.2007.11.009.

Loubere, P., M. Fariduddin, and R. W. Murray (2003a), Patterns of export production in the eastern equatorial Pacific over the past 130,000 years, *Paleoceanography*, *18*(2), 1028, doi:10.1029/2001PA000658.

Loubere, P., M. Richaud, Z. Liu, and F. Mekik (2003b), Oceanic conditions in the eastern equatorial Pacific during the onset of ENSO in the Holocene, *Quat. Res.*, *60*, 142–148, doi:10.1016/S0033-5894(03)00092-9.

Makou, M. C., T. I. Englinton, D. W. Oppo, and K. A. Hughen (2010), Postglacial changes in El Niño and La Niña behaviour, *Geology*, *38*(1), 43–46, doi:10.1130/G30366.1.

Martinson, D. G., et al. (1987), Age, dating and the orbital theory of the ice ages: Development of a high resolution 0-300 000-year chronostratigraphy, *Quat. Res.*, *27*, 1–29, doi:10.1016/0033-5894(87)90046-9.

Philander, S. G. H. (1990), *El Niño, La Niña and the Southern Oscillation*, 293 pp., Academic, San Diego, Calif.

Poveda, G., P. R. Waylen, and R. S. Pulwarty (2006), Annual and inter-annual variability of the present climate in northern South America and southern Mesoamerica, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *234*, 3–27, doi:10.1016/j.palaeo.2005.10.031.

Prahl, F., L. Muehlhausen, and D. Zahnle (1988), Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions, *Geochim. Cosmochim. Acta*, *52*, 2303–2310, doi:10.1016/0016-7037(88)90132-9.

Prahl, F. G., A. C. Mix, and M. A. Sparrow (2006), Alkenone paleothermometry: Biological lessons from marine sediment records off western South America, *Geochim. Cosmochim. Acta*, *70*, 101–117, doi:10.1016/j.gca.2005.08.023.

Rech, J. A., B. S. Currie, G. Michalski, and A. M. Cowan (2006), Neogene climate change and uplift in the Atacama Desert, Chile, *Geology*, *34*(9), 761–764, doi:10.1130/G22444.1.

Rincón-Martínez, D., F. Lamy, S. Contreras, G. Leduc, E. Bard, C. Saukel, T. Blanz, A. Mackensen, and R. Tiedemann (2010), More humid interglacials in Ecuador during the past 500 kyr linked to latitudinal shifts of the equatorial front and the Intertropical Convergence Zone in the eastern tropical Pacific, *Paleoceanography*, *25*, PA2210, doi:10.1029/2009PA001868.

Rundel, P. W., et al. (1991), The phytogeography and ecology of the coastal Atacama and Peruvian deserts, *Aliso*, *13*, 1–49.

Sandweiss, D. H., et al. (2001), Variation in Holocene El Niño frequencies: Climate records and cultural consequences in ancient Peru, *Geology*, *29*, 603–606, doi:10.1130/0091-7613(2001)029<0603:VIHENO>2.0.CO;2.

Schrader, H. (1992), Peruvian coastal primary palaeo-productivity during the last 200000 years, in *Upwelling Systems: Evolution since the Early Miocene*, edited by C. P. Summerhayes, W. L. Prell, and K. C. Emeis, *Spec. Publ. Geol. Soc.*, 64, 391–410.

Shipboard Scientific Party (2003), Site 1229, *Proc. Ocean Drill. Program, Init. Rep.*, *201*, doi:10.2973/odp.proc.ir.201.110.2003.

Sinninghe Damsté, J. S., et al. (2003), A diatomaceous origin for long-chain diols and mid-chain hydroxy methyl alkanoates widely occurring in Quaternary marine sediments: Indicators for high-nutrient conditions, *Geochim. Cosmochim. Acta*, *67*, 1339–1348, doi:10.1016/S0016-7037(02)01225-5.

Skilbeck, C. G., and D. Fink (2006), Data report: Radiocarbon dating and sedimentation rates for Holocene–upper Pleistocene sediments, eastern equatorial Pacific and Peru continental margin, *Proc. Ocean Drill. Program, Sci. Results*, *201*, doi:10.2973/odp.proc.sr.201.108.2006.

Tarazona, J., D. Gutiérrez, C. Paredes, and A. Indacochea (2003), Overview and challenges of marine biodiversity research in Peru, *Gayana*, *67*, 206–231.

Tudhope, A. W., et al. (2001), Variability in the El Niño Southern Oscillation through a glacial-interglacial cycle, *Science*, *291*, 1511–1517, doi:10.1126/science.1057969.

van der Hammen, T., and H. Hooghiemstra (2003), Interglacial-glacial Fuquene-3 pollen record from Colombia: An Eemian to Holocene climate record, *Global Planet. Change*, *36*, 181–199, doi:10.1016/S0921-8181(02)00184-4.

Volkman, J. K., J. W. Farrington, and R. B. Gagosian (1987), Marine and terrigenous lipids in coastal sediments from the Peru upwelling region at 15°S: Sterols and triterpene alcohols, *Org. Geochem.*, *11*(6), 463–477, doi:10.1016/0146-6380(87)90003-9.

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