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]; ~125 kyr 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.


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 <3 mm 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 (151 m 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.

[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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1Auxiliary materials are available in the HTML doi:10.1029/2010GL045728.
attributed to variations in sea level and upwelling strength around the last glacial/Holocene transition and have been unconformities are common on the Peruvian continental shelf 3.5 m (Site 1229 [8]) The record contains a well preserved LH section (upper 2.3 m) consisting of clay-rich diatomaceous 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).

3. Results and Discussion

[8] The record contains a well-preserved LH section (upper 2.3 m) consisting of clay-rich diatomaceous 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://po.dae.c.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) [Schneider, 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 C28 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 C28 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-Otalvaro et al. [2008] who used calcareous nanofossil assemblages at ODP Site 1240 (Panama Basin), and suggested a deepening of the nutrithermocline 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 C28 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 C25 to C35 n-alkanes and n-alcohols concentrations mainly derived from leaf waxes, and (f) concentrations of α-amyрин 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 kyr). The grey bar across the figure refers to the LIG. All molecular fossil concentrations (µg g⁻¹ TOC) 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 (C25 to C35) n-alkanes and n-alcohols that are largely derived from leaf waxes of terrestrial plants [Eglinton and Hamilton, 1967], as well as α-amyрин 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-amyрин 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-amyрин (Figure 2f), and taraxerol (Figure 2f) 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].

[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 [Makov 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 [Garreau 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 Uuyuni, Lake Titicaca, and the Huñaymarca 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 northern-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; Tuthope et al., 2001], the long-term pattern seems to behave different. From a “climate-continuum-point-of-view” periods recognized as interglacial 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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