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El Niño evolution during the Holocene revealed by a biomarker rain gauge in the Galápagos Islands

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ABSTRACT

The El Niño-Southern Oscillation (ENSO) represents the largest perturbation to the climate system on an inter-annual time scale, but its evolution since the end of the last ice age remains debated due to the lack of unambiguous ENSO records lasting longer than a few centuries. Changes in the concentration and hydrogen isotope ratio of lipids produced by the green alga *Botryococcus braunii*, which blooms during El Niño rains in the Galápagos Islands, indicate that the early Holocene (9200–5600 yr BP) was characterized by alternating extremes in the intensity and/or frequency of El Niño events that lasted a century or more. Our data from the core of the ENSO region thus calls into question earlier studies that reported a lack of El Niño activity in the early Holocene. In agreement with other proxy evidence from the tropical Pacific, the mid-Holocene (5600–3500 yr BP) was a time of consistently weak El Niño activity, as were the Early Middle Ages (∼1000–1500 yr BP). El Niño activity was moderate to high during the remainder of the last 3500 years. Periods of strong or frequent El Niño tended to occur during peaks in solar activity and during extended droughts in the United States Great Plains linked to La Niña. These changing modes of ENSO activity at millennial and multi-centennial timescales may have been caused by variations in the seasonal receipts of solar radiation associated with the precession of the equinoxes and/or changes in solar activity, respectively.

1. Introduction

The tropical Pacific atmosphere–ocean system that drives the El Niño-Southern Oscillation (ENSO) is anticipated to change in response to increased radiative forcing from anthropogenic greenhouse gas emissions, with global repercussions (Collins et al., 2010; Pierrehumbert, 2000). Yet the nature and sensitivity of this response is not well understood (DiNezio et al., 2009), partly due to an incomplete knowledge of the underlying climate physics and a lack of paleoclimate data bearing on ENSO variations through time.

Documenting how ENSO evolved through the Holocene in response to known climate forcings is hence crucial for validating model projections of ENSO in the future. Though a wealth of rainfall reconstructions from sedimentary sequences in the tropical Pacific has been produced in an effort to characterize ENSO during the Holocene (see Braconnot et al., 2012 and references therein), those studies remain inconclusive for two reasons. First, the oscillatory nature of ENSO between El Niño and La Niña conditions (Clement et al., 1999) can dampen the signal of inter-annual climate extremes in slowly accumulating sedimentary records since the two opposing modes tend to have counteracting effects on sea surface temperature (SST) reconstructions that average over decades to millennia. Second, it can be difficult to attribute a sedimentary signal unambiguously to one climate phenomenon or the other in locations influenced by both ENSO and seasonal migrations of the Intertropical Convergence Zone (ITCZ) (Braconnot et al., 2012; Koutavas and Joanides, 2012; Leduc et al., 2009a, 2009b; Thirumalai et al., 2013). Corals have sub-annual resolution adequate to reconstruct ENSO, but as they are short lived the most comprehensive composite coral record to date is too under-sampled to document the complete Holocene time period (Cobb et al., 2013). New continuous sedimentary archives and climate proxies that can be unambiguously attributed to ENSO are needed.

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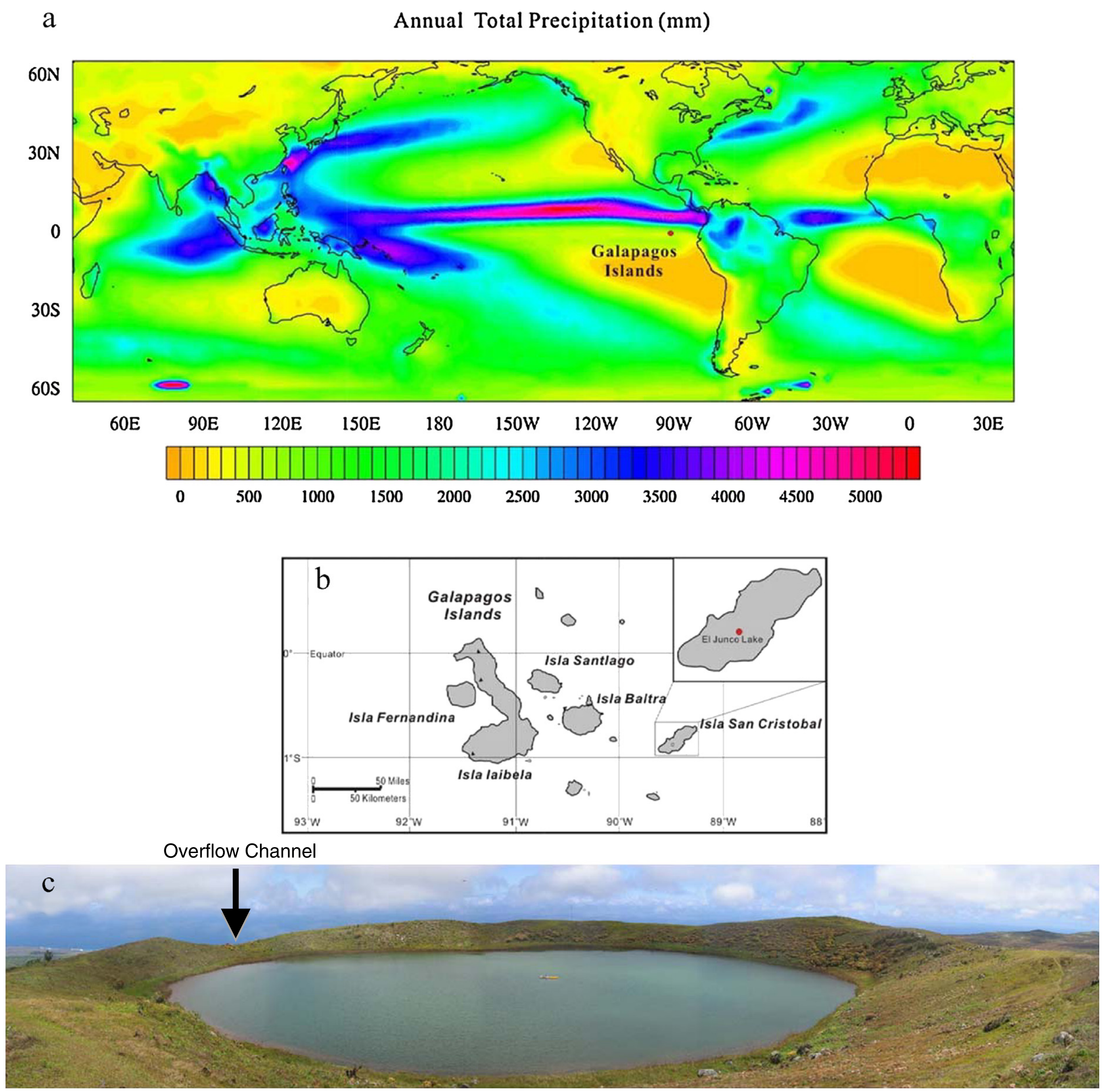

Fig. 1. Tropical Pacific precipitation and the location of El Junco Lake. (a) Map of mean annual rainfall. The location of the Galápagos Islands is shown. The band of heavy precipitation indicates the ITCZ. (b) Map of the Galápagos Islands showing the location of San Cristóbal Island and the position of El Junco Lake. (c) Panoramic photograph of El Junco Lake in September, 2004. The location of an overflow channel is indicated.

Located on the equator ∼1000 km west of Ecuador, the Galápagos archipelago lies south of the modern mean-annual ITCZ position and far from continental climate effects that can complicate the elucidation of coupled ocean–atmosphere processes in paleoclimate records (Fig. 1a). The seasonal climate is characterized by a warm, wet season from January to June, when the ITCZ is nearest to the equator, and a cool, dry season from July to December when the ITCZ is at its northernmost location (Fig. 2). At the height of the warm season in March, the ITCZ splits into northern and southern branches at about the equator, resulting in a bimodal distribution of rainfall with maxima at about 5°N and 5°S, and a relatively dry equatorial zone and Galápagos archipelago during normal years (Gu et al., 2005) (Fig. 2). The persistence of the equatorial cold tongue is the key to this double ITCZ, which vanishes during El Niño events when an intense rainfall band extends continuously from 5°S to 5°N (Gu et al., 2005). El Niño years are thus associated with surges in rainfall in the Galápagos that can exceed rainfall in non-El Niño years by an order of magnitude (Fig. 3).

The only permanent freshwater lake in the Galápagos, El Junco (0.30°S, 91.00°W), lies 670 m above sea level in the closed caldera of an extinct volcano in the highlands of San Cristóbal Island (Fig. 1b, c). With a diameter of 280 m and a depth of 6 m El Junco collects rainwater from a very small catchment (0.13 km^2), and is enshrouded in low-elevation stratus clouds (known locally as garúa) for much of the year. An overflow channel 3 m deep and 2 m wide is evident in the lowest part of the rim (Fig. 1c, indicated by an arrow) (Colinvaux, 1972), but as of this time we are unaware of any confirmed observations of water flowing through the channel. Apart from this overflow and possible seepage through the rim, the lake basin is closed (endorheic).

In a companion paper, Atwood and Sachs (2014) construct an idealized model of the hydrologic balance of El Junco Lake that takes into consideration precipitation, evaporation, seepage, and overflow. They find that the isotope mass balance of the Lake during El Niño warm events is, to a first order, driven by anomalously high precipitation rates rather than by water loss via evaporation, overflow or seepage (Atwood and Sachs, 2014).