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# Holocene environmental change at Laguna Saladilla, coastal north Hispaniola

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ABSTRACT

We inferred environmental changes over the middle to late Holocene in coastal north Hispaniola using pollen, microscopic charcoal, mollusk shells, and diatoms in an 8.5-m sediment core from Laguna Saladilla, Dominican Republic (19°39′ N, 71°42′ W; ~2 m above sea level). Changes in *Rhizophora* (red mangrove) pollen percentages and in mollusk and diatom assemblages indicate major changes in salinity and water depth related to relative sea level rise and possible shifts in precipitation. *Rhizophora* percentages were highest at 7650 cal yr BP, when mollusk shells indicate the lake was connected to the Atlantic Ocean. Laguna Saladilla became progressively brackish ca. 3500 cal yr BP, and transitioned ca. 2500 cal yr BP to its current freshwater condition. High percentages of Amaranthaceae pollen and increased charcoal concentrations over the last ca. 2500 years signal dry climate and increased fires in coastal north Hispaniola. Geomorphological changes over time at Laguna Saladilla partially mask evidence of climate change in the proxies examined, and the record is equivocal before 2500 cal yr BP. Evidence for drier conditions since 2500 cal yr BP is consistent with late-Holocene shifts in the mean position of the Intertropical Convergence Zone (ITCZ) that have been identified on the Caribbean side of Hispaniola. We interpret the record as indicating that ITCZ migratory dynamics may also have affected precipitation on the Atlantic edge of the Greater Antilles.



## 1. Introduction

The Caribbean region has undergone a number of transitions in climate during the Holocene and has been hypothesized as sharing important climate teleconnections with Mexico and Central America over this period (Metcalfe, 1995; Metcalfe et al., 2000). Our knowledge of variations in climate is primarily based on reconstructions from sediment records, but relatively few analyses have been carried out in the Caribbean. Researchers have analyzed lake sediments to characterize changes in climate and environment on the Caribbean islands of Hispaniola (Lake Miragoane: Hodell et al., 1991; Higuera-Gundy et al., 1999; Las Lagunas: Lane et al., 2009, 2011, 2014), Cuba (Laguna de la Leche: Peros et al., 2007a, b), Jamaica (Wallywash Great Pond: Street-Perrott et al., 1993; Holmes, 1998), Puerto Rico (Laguna Tortuguero: Burney et al., 1994), and Grenada (Lakes Antoine and Grand Etang: Fritz et al., 2011), and on Andros Island in the adjacent tropical Atlantic (Church's Blue Hole: Kjellmark, 1996). These studies of lacustrine proxies included various combinations of pollen, charcoal, and isotope analyses, but only Fritz et al. (2011) analyzed diatoms as indicators of environmental change.

We examined diatoms together with pollen, microscopic charcoal, and mollusk shells in the sediments of Laguna Saladilla in the Dominican Republic (19°39′ N, 71°42′ W) to extend knowledge of Holocene climates and environments on the Atlantic edge of the islands of the northwestern Caribbean (Greater Antilles). Laguna Saladilla is a coastal lake located in a very dry region that was relatively underused by humans until the arrival of Europeans. Our record, unlike some others from the region, thus likely reflects primarily natural drivers of environmental change prior to 1492 CE. Our analysis of diatoms in surface and core samples from Saladilla demonstrates their usefulness in documenting salinity changes in coastal lakes arising from changes in climate and relative sea level (RSL).

## 2. Holocene climate and sea level records for the Caribbean

The most widely cited climate reconstruction from the Caribbean islands comes from work on a sediment core from Lake Miragoane, Haiti. Hodell et al. (1991) and Higuera-Gundy et al. (1999) reconstructed changes in the evaporation/precipitation ratio based on oxygen isotope ($\delta^{18}O$) ratios in ostracods and linked these changes to variations in the intensity of the annual insolation cycle in the Caribbean. They proposed that long-term changes in the evaporation/precipitation ratio at Lake Miragoane were principally controlled by Milankovitch (orbitally-forced) variations in insolation (Hodell et al., 1991). A more

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intense annual cycle in the Caribbean from ca. 7000–5300 $^{14}$C yr BP (driven by the greater difference between August and February insolation at 10° N) resulted in higher lake levels and generally wetter conditions at that time (Hodell et al., 1991; Higuera-Gundy et al., 1999). As the intensity of the annual cycle began to decrease after the middle Holocene, water levels in Lake Miragoane began to decrease. Hodell et al. (1991) found a two-step increase in $\delta^{18}$O values beginning ca. 3200 $^{14}$C yr BP that indicated a return to drier conditions by ca. 2400 $^{14}$C yr BP, with a brief period of increased moisture (lower $\delta^{18}$O values) between ca. 1730 and 1000 $^{14}$C yr BP. Pollen and charcoal analyses revealed shifts in vegetation and fire regimes that were generally consistent with the interpretations from isotope analyses (Higuera-Gundy et al., 1999).

Haug et al. (2001, 2003) investigated titanium and iron concentrations in laminated sediments in the Cariaco Basin, on the continental shelf offshore of eastern Venezuela, as a proxy for precipitation. The concentrations of these metals reflect variations in terrigenous input from rivers draining northern South America, and are higher during periods of higher rainfall. Haug et al. (2001, 2003) hypothesized that variations in precipitation inferred from Ti concentrations are closely linked to the mean annual position of the Intertropical Convergence Zone (ITCZ), with a more northerly mean position of the ITCZ resulting in higher precipitation in northern South America and through much of the Caribbean region. The Cariaco data reveal high precipitation during the Holocene thermal maximum from ca. 10,400 to 5400 cal yr BP, followed by drier conditions after 5400 cal yr BP. The late Holocene is characterized by high-amplitude fluctuations that include an extended regional dry period between ca. 1200 and 1000 cal yr BP marked by intense multi-year droughts that may have contributed to the decline of the Maya civilization.

Nyberg et al. (2001, 2002) provided additional marine evidence of high-amplitude shifts in Caribbean climate over the past two millennia associated with ITCZ dynamics. Isotopic analysis of planktonic foraminifera in sediment cores collected offshore of southern and western Puerto Rico revealed fluctuations in sea surface temperatures and salinity on 200–400-year cycles, with minima that coincide with drier periods on the Yucatan peninsula (Nyberg et al., 2002).

On Hispaniola, Lane et al. (2009, 2011) developed pollen and stable carbon and oxygen isotope records from lakes on the southern slope of the Cordillera Central in the Dominican Republic, and found shifts in vegetation and lake level that matched reconstructions of ITCZ position from the Cariaco record, including evidence for arid conditions between ca. 1520 and 890 cal yr BP, with a severe drought ca. 1210 cal yr BP; relatively moist conditions between 890 and 350 cal yr BP; and a return to arid conditions during the Little Ice Age from ca. 350 to 150 cal yr BP. Lane et al. (2014) later carried out compound-specific hydrogen isotope analyses of core samples that confirmed and extended the evidence for arid conditions leading up to and during the Terminal Classic Drought from ca. 1200–850 cal yr BP.

Additional evidence for late Holocene aridity in Hispaniola comes from the Valle de Bao bog in the highlands of the Cordillera Central, where Kennedy et al. (2006) inferred dry intervals between ca. 3700 and 1500 cal yr BP based on poor pollen preservation and lower organic content. Consistently high charcoal concentrations in the Bao bog sediments reveal frequent fires during the late Holocene, probably ignited mainly by lightning in the fire-dependent highland pine forests. Charcoal records from mid- and low-elevation sites on Caribbean islands show more variable temporal patterns, with peaks in fire activity that have been associated with human expansion at Laguna Tortugero, Puerto Rico (Burney et al., 1994) and Las Lagunas in the Dominican Republic (Lane et al., 2009) and with climate shifts at Lake Miragoane, Haiti (Higuera-Gundy et al., 1999).

With the exception of Laguna Tortuguero, located along the north coast of Puerto Rico, and the highland Valle de Bao site, in the upper headwaters of the Atlantic-draining Río Bao, the terrestrial and marine core sites mentioned above are in watersheds facing the Caribbean Sea, or within the Caribbean Sea itself (Fig. 1A). The position of Laguna Saladilla in the north coastal lowlands of Hispaniola offered the opportunity to examine whether inferred shifts in ITCZ position during the late Holocene affected the Atlantic side of Greater Antillean islands.

Laguna Saladilla is only located ~5.3 km from the coast, making sea level change an additional potential driver of limnological change. Changes in sea level could, for example, alter the position of the phreatic zone of the aquifer, or change the susceptibility of the lake to inundation by storm surges and tsunamis. Bard et al. (1990) estimated changes in Caribbean sea level over the past 130,000 yr BP using coral (*Acropora palmata*) from Barbados. Sea level was 118 m lower during the Last Glacial Maximum (ca. 19,000 yr BP), and showed two steps of rapid increase during deglaciation, dated by U–Th at ca. 14,000 and 11,000 yr BP. Based on later analyses of drowned *A. palmata* reefs from multiple sites in the Caribbean and tropical Atlantic, Blanchon and Shaw (1995) identified a third rapid step at ca. 7600 yr BP. They characterized these steps as catastrophic rise events (CREs), and further constrained their timing, amplitude, and duration as follows (all ages are $\pm$0.1 ka, rises are $\pm$2.5 m, and durations are $\pm$50 years): CRE 1: 14.2 ka, 13.5 m rise in <290 years; CRE 2: 11.5 ka, 7.5 m rise in <160 years; CRE 3: 7.6 ka, 6.5 m rise in <140 years. They interpreted CREs 1 and 2 to reflect the collapse of portions of the Laurentide ice sheet, and CRE 3 to reflect dynamics of the Antarctic ice sheet.

Based on radiocarbon dates on peat in Jamaican coastal swamps, Digerfeldt and Hendry (1987) inferred a gradual rate of sea level rise for the last ca. 8000 years. In Cuba, Peros et al. (2007a, 2007b) found evidence of changes in RSL at coastal Laguna de la Leche that affected salinity as well as lake level. They found evidence of higher RSL ca. 4200 cal yr BP, when the lake appears to have been inundated by ocean waters. Expansion of mangroves ca. 1700 cal yr BP, hypothesized to have been facilitated by a decrease in the rate of RSL rise, later separated the lake from direct marine influences. Fritz et al. (2011) documented the effect of rising sea level on aquifer height and lake level at coastal crater lake, Lake Antoine, Grenada, which deepened after ca. 3200 cal yr BP even though this was a period of regional aridity based on the Cariaco Basin titanium record (Haug et al., 2001).

## 3. Site description

Laguna Saladilla is a large (220 ha, 2 m above sea level) freshwater lake located ~5.3 km from the Atlantic coastline in the Dominican Republic (Fig. 1). The site is in one of the drier regions of the country, located in the rain shadow of the Cordillera Septentrional, which lies east of the lake (Bolay, 1997). Average annual temperature is 26.4 °C (World Meteorological Organization, WMO, 2011). Precipitation is estimated to be less than 700 mm per year, and mainly results from polar outbreaks from the north that occur in the autumn and early winter (Bolay, 1997). Lake levels are also bolstered during drier periods by the Río Masacre (also called the Río Dajabón), which flows northward out of the Cordillera Central, where trade-wind-related orographic and convective precipitation dominate. Today the river enters the southwestern end of Laguna Saladilla, but satellite images of the region and ground penetrating radar analyses of the lake sediments (Caffrey, 2011) show that the river channel has migrated over time, sometimes entering the lake at other positions or bypassing it altogether to flow directly to the Atlantic Ocean. Laguna Saladilla presently lacks a well-demarcated surface outlet, but some water flows out through wetlands to the west to reenter a channel of the Río Masacre further downstream. The lake is underlain by, and is separated from the modern Río Masacre estuary by Quaternary alluvium (French and Schenk, 2004), with a northwesterly trending ridge (~38 m above sea level) of upper Cretaceous–post-Eocene marine (limestone) strata that separates the lake from the Río Chacuey ~3 km to the northeast. Mann et al. (1998) inferred that the western extension of the Septentrional Fault Zone, which defines the boundary between the Caribbean and North