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A quantitative inference model for conductivity using non-marine ostracode assemblages on San Salvador Island, Bahamas: Paleosalinity records from two lakes

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ABSTRACT

Quantitative records of past environments are needed to understand natural variability in ecosystems and their responses to climate change. Changes in ostracode assemblages through time can provide such records as ostracode species are sensitive to changes in their local environments. Before they can be used to indicate past environments, however, is it necessary to understand how distributions of assemblages change across environmental gradients. To that end, thirty-two lakes on San Salvador Island, Bahamas were sampled for both ostracodes and nineteen limnological variables. Multivariate fuzzy set ordination indicates that change in ostracode assemblages is significantly and independently correlated with three environmental variables: electrical conductivity (salinity), dissolved oxygen and alkalinity. A transfer function was created to reconstruct past conductivity since changing conductivity of lakes on San Salvador is influenced by changes in climate and sea-level. A 2-component weighted-averaging partial least squares model performed best as a transfer function for conductivity with an apparent r^2 of 0.76 and an r^2 of 0.69 between observed and predicted conductivity, as assessed by leave-one-out cross validation. The resulting transfer function was then applied to two mid- to late-Holocene sediment cores from which ostracode assemblages were sampled. The late Holocene conductivity records show that changes in conductivity of lakes on San Salvador are broadly synchronous with times of enhanced ENSO activity corresponding to elevated conductivity in response to lower Atlantic hurricane occurrence. These results demonstrate that changing ostracode assemblages through time provide a reliable means to reconstruct past salinity and demonstrates the strong effect of ENSO on Bahamian aridity.

1. Introduction

Sedimentary archives from coastal lakes have produced important records of environmental change including: how global cycles affect regional climate patters (Donnelly and Woodruff, 2007; Mann et al., 2009), how sea-level affects local environments (Teeter, 1995; Peros et al., 2007; Gabriel et al., 2009; Kovacs et al., 2013), and how climates have varied through time (Mischke et al., 2014). Limnological conditions are determined by the complex interplay between temperature, precipitation, evaporation, and paleohydrologic conditions, so an understanding of environmental changes and their causes requires a multiproxy approach in a historical context (Peros et al., 2007; Saros, 2009; Sayer et al., 2010). Organism-based calibration datasets can produce high-resolution, quantitative estimates of past environments which allows for the determination of cause and effect relationships (Saros, 2009; Sayer et al., 2010).

Here we develop a robust model to recreate past salinity records from ostracode assemblages contained in lacustrine archives on San Salvador Island, Bahamas. San Salvador is an island with a semi-arid climate where human habitation depends on moisture availability. Additionally, sediments from coastal lakes on San Salvador have produced reliable archives of past hurricane activity (Park, 2012) so if we can understand how past salinity has changed in these lakes, we can understand the relationship between hurricane activity and changes to the local aquatic environment.

The coupled records of hurricane activity and changes to aquatic environments produced by sedimentary archives from San Salvador can provide insight into regional drivers of hurricane activity. El Niño-Southern Oscillation (ENSO) strongly influences tropical cyclone formation in the Atlantic basin with times of strong El Niño resulting in high wind shear across the Atlantic, inhibiting hurricane formation (Gray, 1984; Pielke and Landsea, 1999; Landsea, 2000; Bell and Chelliah, 2006; Nyberg et al., 2007; Klotzbach, 2011; Wang et al., 2014). Times

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of strong El Niño events would thus produce less precipitation in the Bahamas, raising conductivity and times without strong El Niño events would be associated with more hurricanes striking San Salvador, resulting in lowered conductivity in our sampled ponds. Other sedimentary records from the coastal ponds in the Caribbean show this consistent relationship between ENSO and hurricane activity (Donnelly and Woodruff, 2007; Mann et al., 2009).

We present a new calibration set using Ostracoda (Phylum: Arthropoda) from lakes, ponds, and blue holes (cenotes) on San Salvador Island, Bahamas to produce quantitative records of past electrical conductivity from two lakes. Because electrical conductivity is determined by the presence of ions dissolved in the lake water, salinity and electrical conductivity in these lakes measure the same variable and thus are perfectly correlated. Ostracodes are a class of bivalved microcrustaceans that live in all types of aquatic habitats, including the deep ocean and ephemeral pools (Horne et al., 2002). Lacustrine ostracode species live benthic or nekton-benthic lifestyles and are sensitive to changes in the abiotic environment such as salinity, water depth, temperature, or dissolved oxygen concentration (Frenzel and Boomer, 2005). Their low-Mg calcite shells can be preserved as fossils and commonly range in size from 0.5–2 mm and long have been used as biological proxies of anthropogenic change and past environmental conditions (Frenzel and Boomer, 2005; Padmanabha and Belagali, 2008; Michelson and Park, 2013). These organisms have already been used in transfer functions (see Viehberg and Mesquita-Joanes, 2012 for a review) in lake sediments to reconstruct conductivity (Mezquita et al., 2005; Mischke et al., 2007; Mischke et al., 2010a; Mischke et al., 2014; Mercau and Laprida, 2016), water depth (Mourguiart and Carbonel, 1994; Mourguiart et al., 1998; Alin and Cohen, 2003; Mischke et al., 2010b; Peng et al., 2013; Guo et al., 2016), and temperature (Mezquita et al., 2005; Viehberg, 2006).

1.1. Study area

San Salvador is a small (163 km^2) carbonate island located within the Bahamian archipelago in the northern hemisphere-southwest Atlantic (Davis and Johnson, 1989; Fig. 1). Throughout the Pleistocene, dune sediments were deposited across the San Salvador platform during times of elevated sea-level. Many lakes on the island today occur between these ancient dunes, as cutoff-lagoons once open to the ocean, or as karst dissolution-and-collapse features in the carbonate bedrock (Bain, 1991; Teeter, 1995; Park and Trubee, 2008; Park et al., 2014). Salinity in these lakes is controlled by basin geomorphology, degree of connection to the ocean, precipitation-evaporation balance, and climate (Teeter, 1995; Park et al., 2009; Park et al., 2014).

We extracted two sediment cores from lakes on San Salvador: one each from Clear Pond and North Storrs Lake. Comparing these two cores allows us to determine whether changes in conductivity are synchronous across lakes on the island and to relate changes in conductivity of individual lakes to sea-level and/or changing climate (Teeter, 1995).

Clear Pond is a small (0.117 km^2 in surface area), shallow, lake with an ebb-and-flow spring on its eastern shore (Dalman, 2009). Clear Pond's salinity rages from brackish (~20 ppt) in summer and fall to marine-salinity (35 ppt) in winter and spring (Dalman, 2009). Clear Pond was previously a lagoon with a surficial connection to the ocean, but today is isolated from the ocean by mid-Holocene eolianite dunes to the north and unlithified dunes to the south (Park, 2012).

Storrs Lake is shallow, hypersaline, one of the largest lakes on San Salvador (3.2 km^2), and, like Clear Pond, was once an oceanic lagoon (Park et al., 2009; Park, 2012). Its average salinity is 62 ppt, but it can range from 38.5 to 93.5 ppt (Mann and Hoffman, 1984; Mann and Nelson, 1989). The core used in this study was taken from the northern basin of Storrs Lake, the largest of its three basins. Previous cores from these and other lakes on San Salvador show strong within-lake reproducibility of sedimentological signals; when multiple cores are taken from the same basin, the same facies are generally recovered in each core (Park et al., 2009; Park, 2012).

2. Methods

2.1. Field and laboratory methods

We collected surface sediment and water samples from and measured limnological conditions in 32 lakes on San Salvador Island in June 2008, March 2009, and June 2009 (Fig. 1). Surface sediments were collected by sweeping a net (mesh size 2 mm) with attached jar across the sediment-water interface, recovering the upper 1–2 cm of sediment. All samples were collected within the littoral margin, approximately ~10 m from the shore. In a separate study, multiple living communities and death assemblages were collected in seven representative lakes. Except for one lake, Watling's Blue Hole, live/dead agreement in rank-abundance and taxonomic composition was extremely high (Michelson and Park, 2013). Likewise, except for Watling's, little or no variability was found among death assemblages in these lakes (Michelson and Park, 2013). Thus, the ostracodes in the death assemblages collected by net sweeping were determined to represent "modern" assemblages, typical of the lakes from which they were sampled. These core-top death assemblages are also comparable to the time-averaged death assemblages preserved in sedimentary archives that the resulting transfer function was applied to.

Five lake environmental variables were measured in the field with a YSI 556 field meter, including conductivity (±0.5%), salinity (±1%), total dissolved solids (±4 g/L), dissolved oxygen (±2%), and water temperature (±0.15 °C). Alkalinity was determined in the field using a Hach methyl orange and phenolphthalein (total) acidity digital titration kit (±0.1 mg/L as $CaCO_3$). Water depth at each site was measured to the nearest cm using transect tape and a measuring stick. Latitude and longitude as well as lake area were determined using the San Salvador GIS database (Robinson and Davis, 1999) and a hand-held GPS unit.

We filtered sediments using 125 μm (φ-size 3) and 63 μm (φ-size 4) sieves with deionized water. Upon drying, ostracode death assemblages were picked using a dissecting microscope. In all cases, at least 400 ostracode valves were picked from the >125 μm fraction of each sample and all adults were identified to species level using reference collections at the University of Akron (Trubee, 2002; Park and Trubee, 2008).

Water samples were analyzed for the concentration of major cations using a Perkin Elmer Analysis 700 atomic absorption (AA) spectrometer at the University of Akron. Water samples were analyzed for chloride and sulfate anions using a Dionex DX-120 ion chromatograph. All major ions concentrations are expressed as mg/L.

Sediment cores were extracted from two lakes on San Salvador and assessed for ostracode assemblages, sediment loss on ignition, and grain size. One 1.23 m core was extracted from Clear Pond (Dalman, 2009), and one 1.62 m core was extracted from the north basin of Storrs Lake (Fig. 1).

Cores were extracted by push-coring techniques, in 2-inch-diameter black acrylonitrile-butadiene-styrene (ABS) tubing, and split and stored in the University of Akron's refrigeration facility. No sediment compaction was evident in either of these cores during coring or extraction. The cores were sampled at 1 cm intervals for ostracode assemblages using standard freeze-thaw techniques (Delorme, 1989; Danielopol et al., 2002).

Sediment loss on ignition was done at 1 cm intervals using standard methods (Heiri et al., 2001). Sediment grain size was analyzed at 1 cm intervals using a Malvern 2000 Mastersizer at Kent State University. Sediment samples were unprocessed other than being sieved to <1 mm before grain size distribution was determined. Grain size was expressed as percent medium to fine sand (62.5 μm–1 mm) of the sample by volume.

Records of potassium (K) were obtained as a proxy for African dust deposition by X-ray fluorescence of the Clear Pond and North Storrs