PROCEEDINGS OF THE 14TH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
Fredrick D. Siewers and Jonathan B. Martin

Production Editor:
Fredrick D. Siewers

Gerace Research Centre
San Salvador Island, Bahamas
2010

Front Cover Photograph – "Kelly and the Veggiemorphs" courtesy of Jon Martin

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A & A Printing Inc., Tampa, FL

ISBN 0-935909-90-7

TRACKING STORMS THROUGH TIME: EVENT DEPOSITION AND BIOLOGIC RESPONSE IN STORR'S LAKE, SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

Because of its position within the southwestern Atlantic Ocean, San Salvador has been the site of many hurricane strikes throughout its history. As such, it remains an effective setting in which to examine hurricane intensity in the Late Holocene. Storr's Lake, like many of the lakes along the island's margin provide a depositional archive recording the paleotempestites from these storm events. This study addresses the following questions: 1) What is the depositional history of Storrs Lake through the last 3,000 years and 2) Can we see large storm events in the sediment record and determine the biologic response to these events?

Cores varying in length between 5 to 200 cm were recovered from two transects across the Fortune Hill basin in the southern part of Storr's Lake. The cores were analyzed for organic and carbonate content, dry bulk density, grain size, chemical composition, sediment fabric, trace elements, spectralphotometry, ostracode and mollusk faunal composition. Large storms can be identified in these cores by a distinct increase in grain size and a change in dry bulk density. Allochthonous sand found within the cores match the sand found on the dune faces adjacent to the lake and are identified as storm wash-over deposits. Biologic patterns suggest that species richness and abundance change after these large storm events, possibly due to the freshening that occurs from the storm and a change in the basin substrate. Cyanobacterial mats that are prevalent throughout many of the lakes on San Salvador also have a documented response to these freshening events by a community shift and increase in productivity. The cores record a major climatic shift occurring approximately 700 ybp and which is contemporaneous with colonization of the island. There is evidence of a hurricane 'hyperactivity period' from 1000 – 3000 ybp that has been identified in other records along the Gulf Coast of North America.

INTRODUCTION

Storr's Lake

Storr's Lake is a large cutoff lagoon located on the east coast of San Salvador island (Figure 1) that trends north-south and is 7.3 km long with an area of 3.2 km^2 and a maximum depth of 2 m (Mann and Hoffman, 1984). Lake salinity averages 62 ppt and has an average alkalinity of 3.34 meq (Mann and Hoffman, 1984).

Storr's Lake is separated into three distinct basins by bedrock highs oriented along strike (Titus, 1984). These sub-basins have been separated and connected at different times throughout its history by sea-level fluctuation. Approximately four thousand years ago, the lake was an open tidal lagoon, much like modern-day Pigeon Creek, and a N-S trending channel developed through the middle of the basin (Titus, 1984). Sea-level fluctuation caused these basins to be separated at times, and as a result, they have distinct chemistries and depositional histories (Corwin, 1985, McNeese, 1988, and Zabielski, 1991). It is estimated that the north basin remained open for nearly 1000 years until it abruptly closed, possibly through spit progradation (Zabielski, 1991). The central basin closed approximately one thousand years later through similar processes (McNeese, 1988). It is unknown when the southern basin closed (i.e. Fortune Hill Basin) or if it was ever open to the ocean. Once the sub-basins closed, the lake quickly became hypersaline and algal mats began to develop (Figure 2).

The bedrock separating the north and central sub-basins is a meter lower than that separating the central from southern basin. The north and central basin reconnected and acted as one lake long before the Fortune Hill Basin formed (Corwin, 1985). Because of this isolation, the Fortune

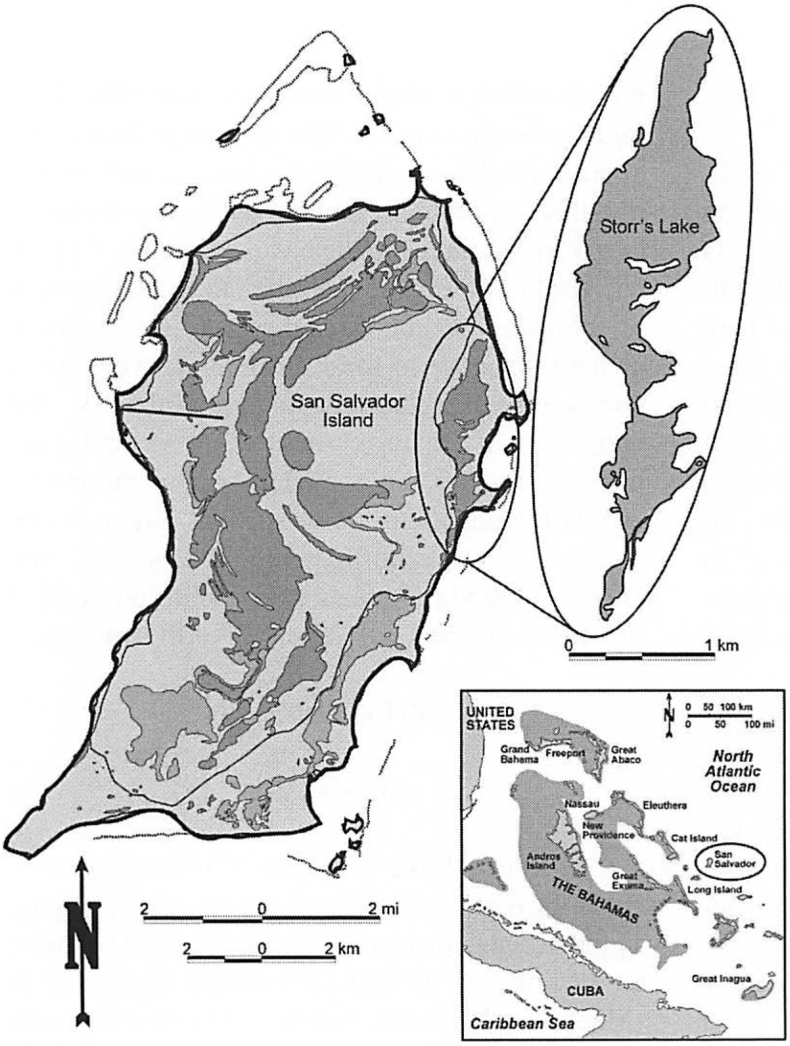

Figure 1. Location map of San Salvador Island and Storr's Lake. Dotted lines represent fringe reefs. Robinson, M. C. and Davis, L. R., 1999 San Salvador Island GIS database.

Hill Basin has a substantially different sedimentological record than the other sub-basins of Storr's Lake (Figure 3).

The northern part of Storr's Lake is currently connected to the ocean through conduits or lake drains, and consequently, lake levels fluctuate daily with the rise and fall of the tides (Mann and Hoffman, 1984). The lake levels also respond to intervals of greater precipitation (Mann and Nelson, 1989). The majority of precipitation percolates into the ground and recharges the lake (Mann and Nelson, 1989). Total lake-level fluctuations during periods not influenced by large storm events tend to range from 21-26 cm (Mann and Nelson, 1989).

The lake ranges from pink to reddish brown in color due to suspended organic matter and cyanobacteria that thrives in many of the Bahamian Lakes, particularly the hypersaline ones (Teeter, 1985). The lake is very turbid, having no visibility past a few centimeters even at times of high water levels. The lake is surrounded by dense mangroves and much of the lake floor is covered with an organic-rich calcareous ooze (Mann and Nelson, 1989).

Storr's Lake Biota

The extreme environmental conditions found in Storr's Lake do not support high faunal diversity. The high salinity and temperatures do not allow for abundant life throughout the lake. Ostracodes, algae, cyanobacterial mats and brine shrimp have been found in the modern lake (Dakoski and Bain, 1984). In most cases, the ostracodes from lakes on SSI can be divided into faunal associations based on salinities that can then be used as proxies for paleoenvironmental change (Sanger and Teeter, 1982; Teeter, 1985; Teeter and Quick, 1990; Park and Beltz, 1998; Park and Trubee, 2008). Teeter (1985) found that the lakes on SSI preserve a record that could be correlated with global climate change records. In these prior studies, preliminary evidence is presented

Figure 2. Photograph taken in June 2007, on top of the dune separating Storr's Lake from the ocean, looking north.

to suggest that lower salinity levels, as recorded by the ostracodes, can be correlated with sea-level lowstands, increased precipitation, or temperature decreases, which are all linked to climate change (Teeter, 1995).

The hypersaline lakes that are found along the eastern side of the island, such as Storr's Lake and Salt Pond, are well-known for their prokaryotic cyanobacterial communities that form laminated mats. These mats comprise the autochthonous portion of the bottom sediments of these lakes (Paerl et al., 2000; 2003; Yannarell et al., 2007). Oxygenic cyanobacterial phototrophs and closely associated heterotrophic bacteria dominate these mat layers. Anoxygenic photosynthetic bacteria as well as associated microbes live in the deeper, anoxic, sulfide-rich layers (Pearl et al., 2003). Since lake levels fluctuate with seasonal rainfall, the edges of the mat can get exposed and periodically desiccated.

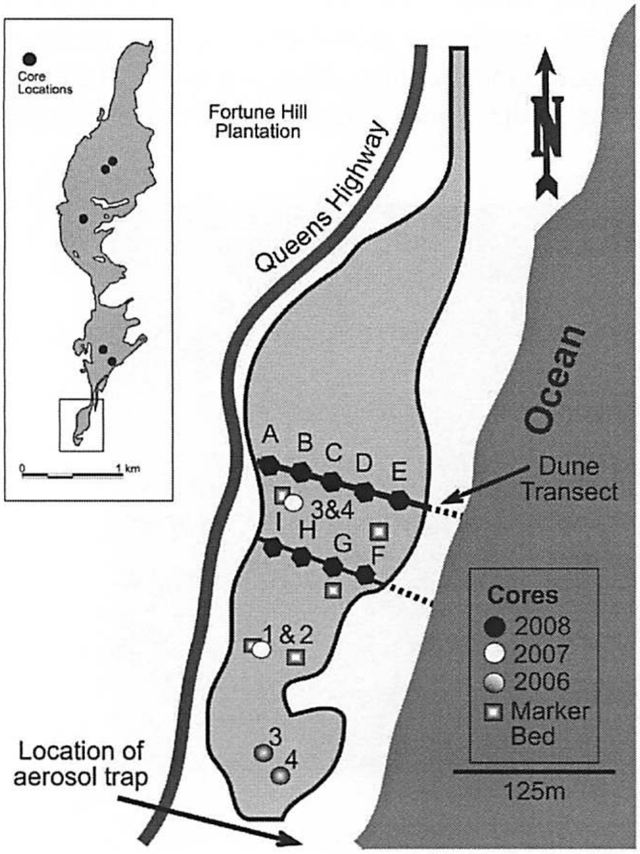

Figure 3. Map of Fortune Hill Basin, southern part of Storr's Lake showing dune transects, coring transects and marker beds.

Cyanobacterial mats are colonies of several different species of bacteria that coexist within the mat ecosystem and are dependant on one another for photosynthesis and nutrient cycling (Gemerden, 1993). Mats that grow undisturbed for long periods of time develop regular laminations though it is still uncertain whether or not these laminations represent seasonal changes, or population changes (Jorgensen et al., 1983; and Gemerden, 1993). With the addition of a sandy substrate and periods of exposure, cyanobacterial mats can form lithified stromatolites. Without the exposure and change in substrate, the mats continue to grow on top of each other.

Paerl et al., (2003) monitored the photosynthetic CO_2 and N_2 fixation in March 1999, 2000, and 2001 and found that after large storm events like hurricanes, Salt Pond experienced a 'freshening' that lead to increased productivity and substantial mat growth (Paerl et al., 2003). Paerl et al., (2003) and Yannarell et al., (2007)

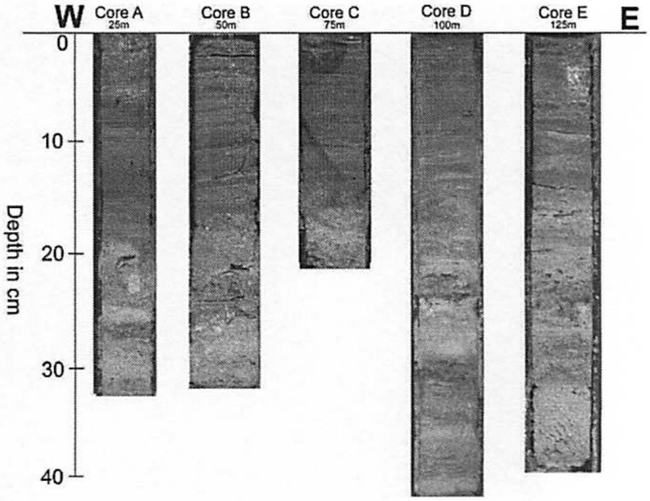

Figure 4. Photographs of cores in BA07SL T1 from Storr's Lake Fortune Hill Basin 2007.

documented community shifts in the cyanobacteria following disturbances such as hurricanes.

San Salvador Island Climate

The Bahamian Archipelago lies within the sub-tropics and typically has warm temperate winters and hot tropical summers. The amount of precipitation received is not equitably distributed and is highly dependent on the location of the Bermuda High. Even the precipitation patterns on small islands such as San Salvador varies temporally and spatially (Gamble, 2008).

Increased hurricane activity 3400-1000 ybp in Caribbean has been reported throughout the Gulf Coast and through the Caribbean from core records (Liu and Fearn, 2000). These dates correspond to two rapid climate change events that indicate warmer, dryer climates that would be conducive to increased hurricane occurrences. Recent data by Gamble (2008) shows how the positioning of the Bermuda High can dramatically affect precipitation and climate throughout the Caribbean on an annual scale. This new information further supports the idea of high climate variability through the Holocene in the Tropics as well as demonstrating the direct relationship between the Bermuda High and Bahamian precipitation patterns (Gamble, 2008; Gamble, 2010).

In early May, the Bermuda High is strengthened as solar radiation increases across continental landmasses through the Northern Hemisphere and the oceanic anticyclone expands west (Davis et al., 1997). Hurricanes are likely to follow the movement of the Bermuda High along the western edge where there is heavy rainfall (Keim, 1997). Extraordinarily warm summers strengthen the Bermuda High indicating that incoming solar radiation could affect the number of intense hurricanes through the Caribbean and along the Gulf Coast (Coleman, 1988; Liu and Fearn, 2000). The geologic record indicates that there has been a phase/ anti-phase relationship through the Holocene with respect to hurricane strikes and the position of the Bermuda High (Liu and Fearn, 1993, 2000; Scott et al., 2003). This indicates that it may be possible to correlate paleo-hurricane deposits with global climate change (Liu and Fearn, 2000; Anthes, et al., 2006; Emanuel and Mann, 2006).

Hurricanes

San Salvador Island (SSI) is particularly susceptible to hurricane activity because of its location at the easternmost part of the southwestern Atlantic Ocean. Hurricanes commonly cross the Bahamian Archipelago as they enter or exit the region, and as a result, the Bahamas experience more hurricanes than any other area in the Atlantic. From 1851 until 2008, the Bahamas have experienced 118 hurricanes with 19 crossing directly over SSI (NOAA Historical Hurricane tracks, Shaklee, 1996).

In 2004, Hurricane Frances, a category 4 hurricane, tracked directly over SSI. It made initial landfall on the southeast side of the island with winds reaching 233 km/hr and a storm surge of about 5 m (Niemi et al., 2008; McCabe and Niemi, 2008). The island experienced substantial damage from which the residents are still recovering.

METHODS

Piston and Push Coring

Twenty one cores were collected between the years 2006-2008 from various locations throughout Storr's Lake (Figure 3). They were recovered by Livingstone piston, or push-coring techniques. All cores were collected and stored in 2 inch diameter black ABS piping. Cores were transported to the University of Akron and split and stored in the department's walk-in refrigeration facility.

Loss on Ignition

Cores were sampled and processed every centimeter for carbonate and organic matter using loss on ignition techniques. One cubic centimeter of sediment was placed into a ceramic crucible and weighed. The crucible was then placed into a drying oven at 105°C, dried for a period of approximately 24 hours, and weighed again to determine wet and dry bulk density and water content (Boyle, 2001). The crucibles were then placed into a muffle furnace and baked at 550°C for a period of 4 hours to remove organic matter. After cooling, the samples were re-weighed and then baked again at 1000°C for two hours to determine the carbonate content (Boyle, 2001).

Grain Size

Each centimeter of core was processed to determine sediment grain size using a Malvern Mastersizer 2000 laser diffractometer housed at Kent State University. Sediment was added to deionized water and sonicated for two minutes to obtain an obscuration of around 10-30%. Five readings were taken for each interval and then an average reading was used for data analysis. Coarse grain sizes were used as the main proxy for hurricanes because those grain sizes were associated with transported (allogenic) marine sediments from the adjacent ocean.

Microfossil Analysis

To sample for microfossils, one cubic centimeter of sediment was taken from each centimeter interval and processed using established freeze-thaw methods (Forester, 1990). Each sediment fraction (fine—80 microns and coarse—230 microns) was examined under an Olympus SZ30 binocular microscope. Microfossils were removed and placed on micropaleo slides. Mollusks, gastropods, and foraminifera were counted for each interval. Only the right valves of adult ostracodes were identified and counted.

Spectralphotometry

All of the cores were examined at the cm scale using a Minolta CM-2600d / 2500d portable Spectrophotometer house at Kent State University to obtain spectrophotometry data at the centimeter scale for all of the cores. Spectralphotometry provides quantitive measurements in three dimensional color spaces (L*, a*, b*) that can reveal very detailed changes in bulk material properties (Blum, 1997).

The L* measurement by the photospectrometer is a calculation of luminescence from light reflected off the surface of the core. The luminosity of the cores is dependent on color and thus L* correlates well with percent sand because the sandy layers are much lighter than the microbial mats. The a* is a measure of the red (positive)/green (negative) color coordinates, which is proxy for oxidation in microbes and minerals (Kokaly et al., 2007; Sellitto et al., 2007; Ben-Dor et al., 2008) and may be linked to productivity (Ortiz et al., 2003). The b* is a measure of blue (negative)/yellow (positive) color coordinates which is a proxy for sulfides and may indicate reducing environments (Ortiz et al., 2003).

Radiometric Dating

Organic material was obtained from three cores using a small spatula and sent to Beta Analytical Labs for analysis. AMS carbon dates were calculated for four different depths on four different cores. Core BA06 2B was sampled at the top of the peat layer at 120 cm. Core BA07 LT1 D was sampled at 33 cm for organic material; core BA07 LT2 H was sampled at 26 cm for mangrove and other leaf material; core BA08SL 3A was sampled at 11 cm for mangrove and other leaf material. The dates were then calendar year calibrated using CalPAL online (www.calpal-online.de).

The top four centimeters of core BA07SL – D were sampled for the presence of Cesium – 137 at Western Kentucky University. Cesium - 137 was released into the atmosphere and deposited world wide through nuclear testing that occurred in the 1950's and 1960's. The test was done on bulk material from one centimeter intervals. A weak Cs^{137} signal (100 counts over two days – barely above background) was obtained from the uppermost 1 cm of the core. Core D was chosen because it was near the center of the basin, but not in the channel.

RESULTS

Descriptions of Core Facies

The cores have consistent facies that are commonly found throughout each core (Figure 4 and 5). This is a general description of the cores based on the overall core composition. In each core, nearly 100% of the sediments are composed of carbonate materials. The top 15 cm is dominated by microbial mat laminations and carbonate mud (Figure 5). The mat laminations vary in color and thickness. Small amounts of organic material can be found sporadically throughout, although most of it is unidentifiable and there is not enough material to obtain radiocarbon dates. The mat laminations and carbonate mud have a gelatinous texture from high water content and biological activity. There are very thin sand layers ~ 1 mm thick within some of these mat layers.

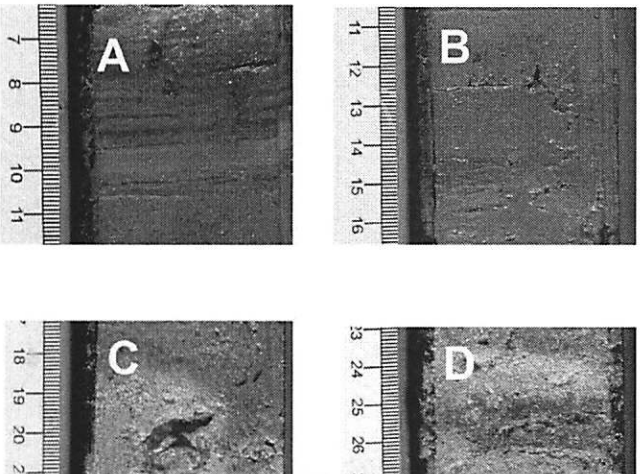

Figure 5. General core facies photographs taken from BA07SL-A. A. Cyanobacterial mats; B. Carbonate mud; C. Lithified sand layer; D. Stacked sand deposits with high amounts of evaporite minerals. Scale in cm.

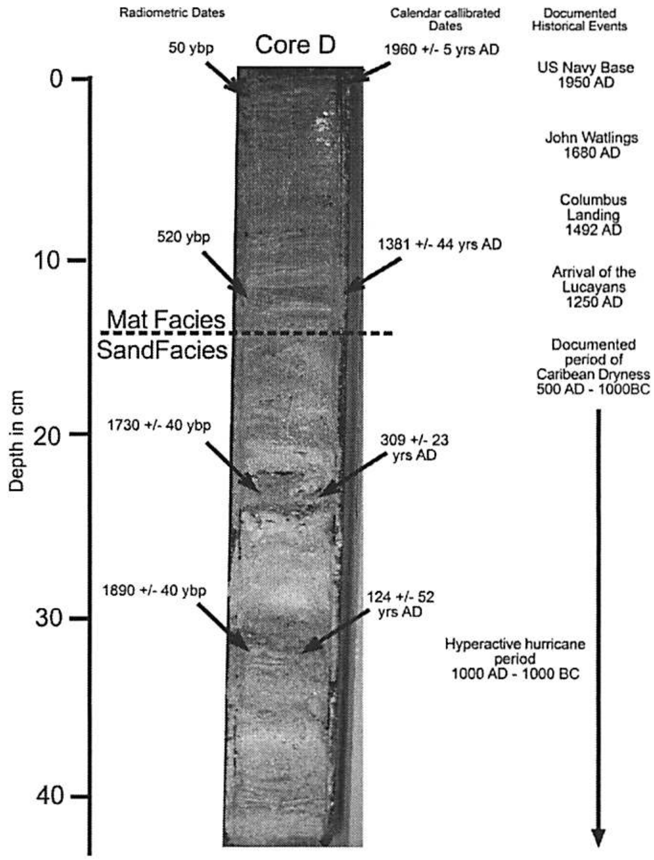

Figure 6. Location dates integrated into Transect 1 Core D. Radiometric dates are on the left of the core and calendar calibrated dates are on the right (calpal-online.de/). A chronology of documented historical events is on the far right and sequenced with age model (Rose, 1982; Berman and Persall, 2000; Liu and Fearn, 2000; Mayewski et al., 2004; Gerace et al., 2007).

There is a lithified sand crust layer at a depth of about 20 cm across the entire Fortune Hill basin. This layer can be seen in each of the cores and ranges in thickness from 1-3 mm (Figures 4 and 5). This crust became a limiting factor at times during coring because we were unable to push through to fill the entire core barrel.

The remainder of the core is composed primarily of repeated sand deposits with scour surfaces between the beds (Figure 6). These deposits vary in thickness, color and the percentage of sand to other materials. Between some of these sand deposits there is microbial mat growth but it never exceeds a thickness of a few millimeters and in most instances, development is very weak. Large crystals of gypsum and halite are seen in many of the sand intervals as well as marine shells of mollusks and gastropods ranging from 0.5 – 5 mm in length.

Core Loss on Ignition (LOI)

Loss on ignition was performed on all cores taken. Results from these analyses indicate that the intervals that are dominated by microbial mat facies are correlated with higher organic matter except where there is inter-bedded sand (Figures 7 – 10). When sand is present in the mat layers, there is often a peak in the CO_3 content. Organic matter is low in the sandy facies except where there is evidence of microbial mat development. Dry bulk density is correlated to the sandy layers and water content increases where there are microbial mats (Figures 7 - 10).

Core Grain Size Analyses

Grain size is an effective proxy for recognizing hurricane deposits in lake cores (Liu and Fearn 2000, Donnelly and Woodruff, 2007, Park,

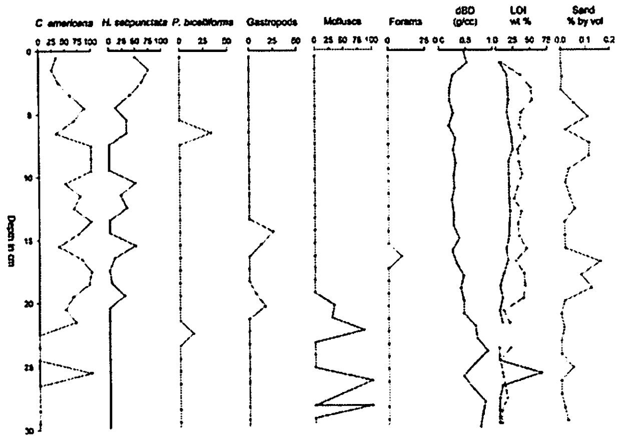

Figure 7. Composite analytical data sets for BA07 A. Ostracodes C. americana, H. setipunctata, P. bicelliforma, gastropods, mollusks and forams (plotted as % of total microfossils) as well as dry bulk density, loss on ignition (dashed line represents CO_3; solid line represents organic matter (OM)) and sand peak (250 μm) % by volume. Dashed horizontal line indicates transition from mat facies into sandy facies.

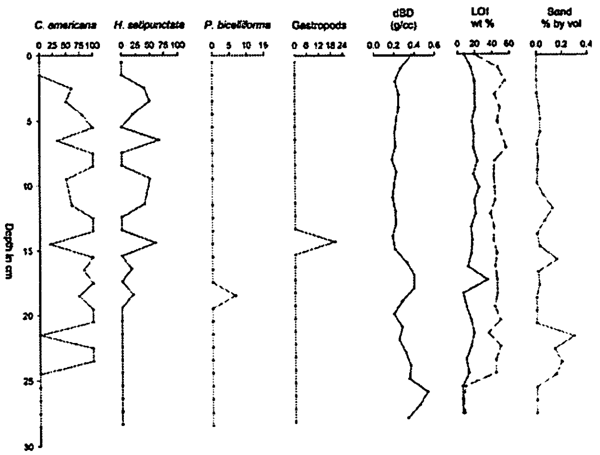

Figure 8. Composite analytical data sets for BA07 B. Ostracodes C. americana, H. setipunctata, P. bicelliforma, gastropods, mollusks and forams (plotted as % of total microfossils) as well as dry bulk density, loss on ignition (dashed line represents CO_3; solid line represents organic matter (OM)) and sand peak (250 μm) % by volume. Dashed horizontal line indicates transition from mat facies into sandy facies.

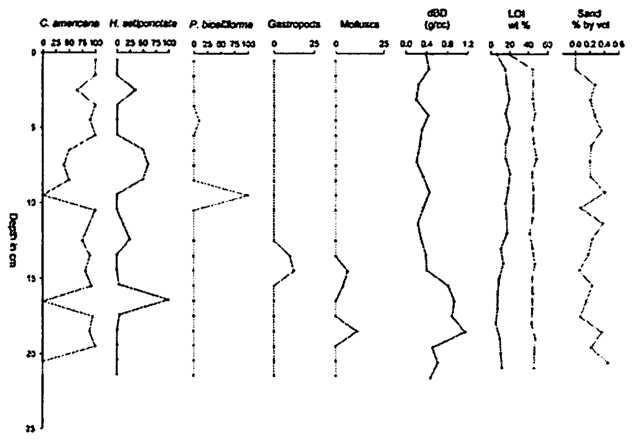

Figure 9. Composite analytical data sets for BA07 C. Ostracodes C. americana, H. setipunctata, P. bicelliforma, gastropods, mollusks and forams (plotted as % of total microfossils) as well as dry bulk density, loss on ignition (dashed line represents CO_3; solid line represents organic matter (OM)) and sand peak (250 μm) % by volume. Dashed horizontal line indicates transition from mat facies into sandy facies.

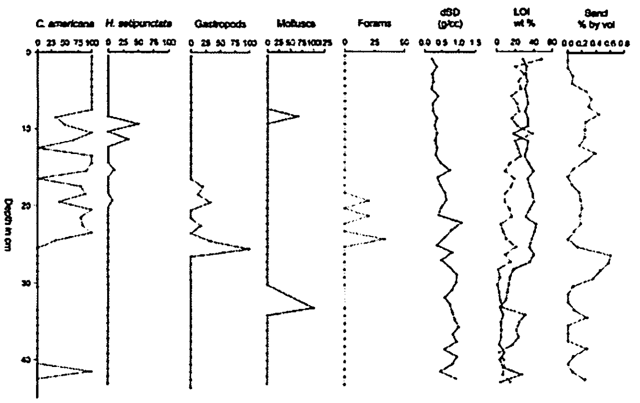

Figure 10. Composite analytical data sets for BA07 D. Ostracodes C. americana, H. setipunctata, P. bicelliforma, gastropods, mollusks and forams (plotted as % of total microfossils) as well as dry bulk density, loss on ignition (dashed line represents CO_3; solid line represents organic matter (OM)) and sand peak (250 μm) % by volume. Dashed horizontal line indicates transition from mat facies into sandy facies.

et al., 2009,). As found by Park et al., (2008; 2009), the sand located on the beach that separates Storr's Lake from the ocean consists of very well sorted, sub-angular skeletal sand (Figure 11). Sand analyzed for grain size demonstrates a very well defined peak 250 μm. When this grain size is plotted as percentage of the whole by volume and compared across the basin, the sand peaks correlate across the basin and the sand bed thickness gets larger across the transect as the cores become more proximal to the ocean (Figure 11).

Core Microfossil Analyses

Mollusks, foraminifera and gastropods are allochthonous biota that could not survive in Storr's Lake under hypersaline conditions (Figure 12). They are found in several sandy intervals of each core, along with ostracodes which do reside within the lake under normal conditions. Ostracodes were found in most intervals but there is a sharp decline in abundance through sandy intervals with the presence of marine fauna, and no ostracodes are found in sandy intervals with the presence of evaporate minerals (Figures 7 - 10). Only two ostracodes are abundant in Transect 1 (*C. americana* and *H. setipunctata*). These species have the highest salinity tolerance found in lakes on SSI (Park and Trubee, 2008). There is a strong inverse correlation between these two species but *H. setipunctata* does not occur in all intervals where there documented decline of *C. americana*. The inverse relationship and community change is only present in intervals where there are sandy layers with marine fauna (Figure 12).

Core Spectrophotometry

Both the a* and b* are strongly correlated and can be interpreted as a measure of oxidation and reduction. There is a positive correlation between oxidation and increased amounts of sand in the core through the mat facies possibly indicating an increase in productivity by cyanobacterial

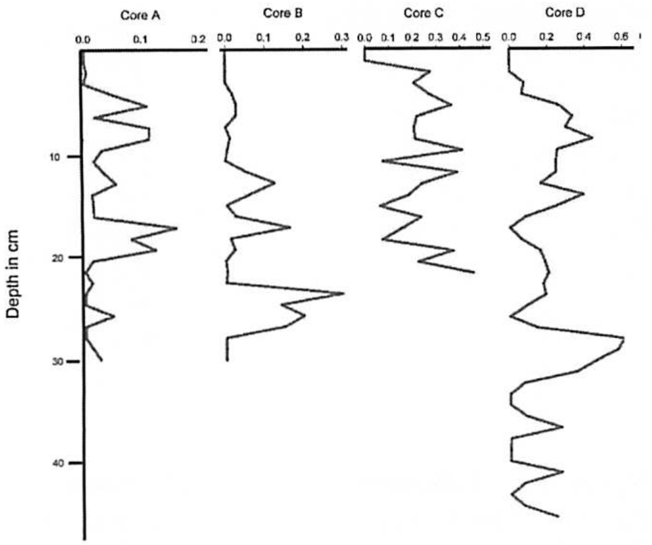

Figure 11. Percent of beach sand by volume plotted across A - D Transect 1 cores. Sand packages become larger and more pronounced proximal to the ocean.

mats connected to hurricane wash over. Directly after, the sandy facies there is an negative correlation between oxidation and sand. This indicates a change in the bulk material due to change in the mode of deposition. (Figure 13).

Radiometric Dates

Core BA06 2B taken from the center of the northern basin returned a date of 3870 +/- 40 ybp at 120 cm depth. A date of 1890 +/- 40 ybp (cal. 124 +/- 52 yrs AD) was obtained from an organic rich mat layer in Core D at 33cm depth. The top of this core was also analyzed for the presence of cesium which was found within the top one centimeter of sediment. Core H; Transect 2, 22 cm yielded a date of 1730 +/- 40 ybp (cal. 309 +/- 53 yrs AD) on mangrove leaf fragments. This core was taken approximately 50 m south of Core B and from similar organic material at the same interval. Core 3A taken through a marker bed directly adjacent to Core H yielded a date of 520 +/- 40 ybp (cal. 1391 +/- 44 yrs AD) at a depth of 11 cm from a mangrove leaf. Both of these dates can be integrated into Transect 1 through Core B and a general sedimentation rate can be created for the 15 cm of mat accumulation of 1 cm/ 45 yrs (Table 1, Figure 6). The presence of cesium in only the top one centimeter of core material indicates that at least 45 years (cal. Year 1960) are represented in the top one centimeter, and that this sedimentation rate may be a fairly accurate calculation.

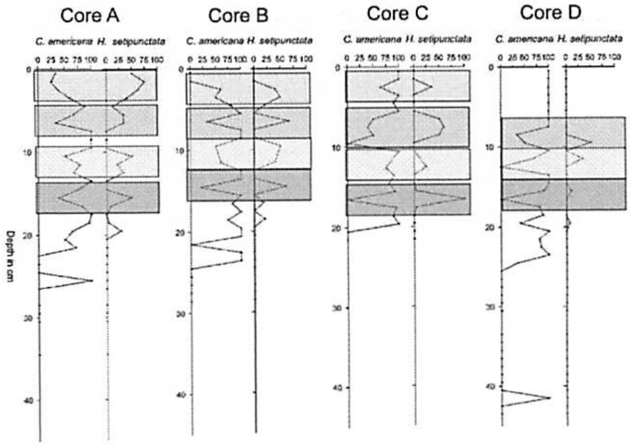

Figure 12. Inverse correlation of C. americana and H. setipunctata abundance within cores BA07-A-D plotted as percent of total ostracodes. Colored boxes indicate community shifts occur which correlate across the transect.

DISCUSSION

Marine sediment can record oceanic conditions and provide valuable information about currents and atmospheric circulation patterns from which we can interpret global climate. This information can provide important insight on past environmental conditions. Terrestrial records can be the key to local conditions but high-resolution studies are often difficult or impossible due to surface weathering, hiatuses, and diagenetic changes. Lakes provide and alternative to terrestrial records because local environmental conditions are more apt to be preserved in lake bottom sediments., Information obtained from lake cores can provide high resolution data pertaining to local environmental and global climatic changes.

The record found in the southern basin (Fortune Hill) of Storr's Lake reveals a major shift in deposition that corresponds to a shift in climatic conditions occurring at approximately 700 ybp when the 1cm/45yr sedimentation rate is applied. Hurricanes can be identified within the geologic record through a change in grain size and the presence allocthonous material.

From this study, it is clear that hurricanes can be identified within the geologic record from lake cores on San Salvador Island. Being able to identify paleohurricanes and their relative intensity over time is important because it can be linked to climatic conditions and positioning of the Bermuda High, which can provide important information in climate modeling. The IPCC (2007) states that increasing temperatures and green house gasses will affect the strength and position of the NOA (Delworth and Dixon, 2000). This shift, along with warmer ocean temperatures, may make conditions conducive once again for a hyperactive hurricane period throughout the Caribbean.

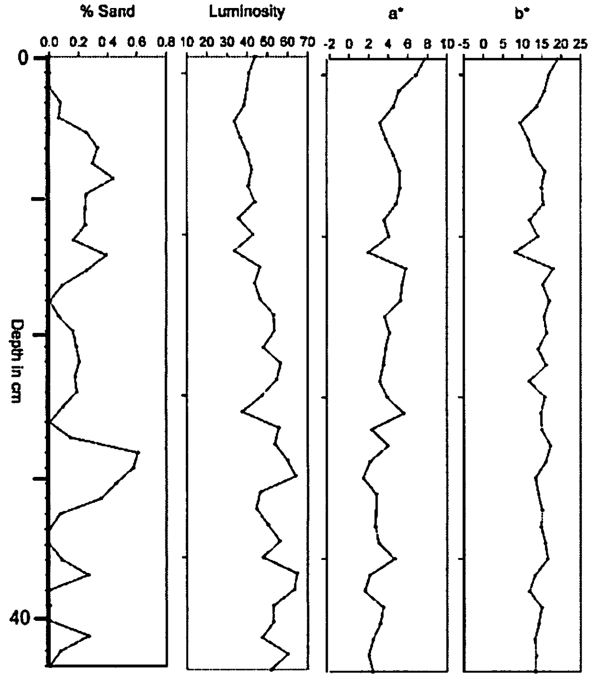

Figure 13: Core spectrophotometry: Luminosity (L), a* and b* plotted with percent beach sand from BA07-D to show increase in luminosity and patterns of oxidation and reduction with storm deposits in mat facies. Positive values on a* indicate an increase in oxidation and negative values on b* indicate an increase in sulfide production. Dashed line indicates the change from mat facies*

There are two distinct modes of deposition within the Fortune Hill basin of Storr's Lake that change abruptly around 700 ybp (15 cm depth). The period before 700 ybp indicates more arid conditions can reasonably be interpreted to be indicative of an arid climate based on the lack of algal mat development and the presence of evaporite minerals. If the increase of sandy facies was indicating marine or surf environment, there would be more marine fauna present in the core. Instead, the marine fauna is only present in certain intervals throughout the sandy facies. Additionally, the high concentration of evaporites indicates that the basin was closed. The sandy facies occurring at 700ybp corresponds to a known rapid climate change (RCC) event from arid to moist environments that has been documented from paleoethnobotanical data in soil and lake cores on SSI (Berman and Persall, 2000; Marchant and Hooghiemstra, 2004).

This change corresponds to the known time period that the Lucayan people began to colonize San Salvador once the climate shifted to create enough annual precipitation to sustain freshwater reservoirs. The increased precipitation connected inter-dunal lakes, creating an effective trade and transportation system that was used by the Lucayans and subsequent inhabitants (Berman and Pearsall, 2000).

The upper 15 cm of the cores consists of laminated cyanobacterial mats. There are three relatively evenly spaced sand peaks throughout this interval at similar depths in the transect because the sand was found in all cores across the lake basin, these storms must have been extremely powerful, in the range of a CAT 4 or 5 hurricane. Assuming relatively constant deposition, a sedimentation rate can be calculated of 1 cm/45 yrs

Table 1. Radiometric dates and location on core. Calendar years of radiocarbon dates calibrated through Cal pal (www.calpal-online.de).

Core name	Type of date	Depth	Age	Calendar yr AD
BA07 SL D	Cesium - 137	1 cm	50 +/- 5	1960 +/- 5
BA07 SL D	Radiocarbon	33 cm	1890 +/- 40	124 +/- 52
BA07 SL H	Radiocarbon	22 cm	1730 +/- 40	309 +/- 53
BA07 FHB 3A	Radiocarbon	11 cm	520 +/- 40	1381 +/- 44

and a recurrence interval can be estimated for one CAT 4-5 hurricane every 233 yrs. Looking into the historical record, there has been one CAT 5 and five CAT 4 hurricanes passing near SSI within the last 157 yrs (Shaklee, 1996). The rate of occurrence was much higher during the 1930's—a time that corresponded with the Dust Bowl in the North American mid-continent. It has been hypothesized that the increased frequency and intensity of hurricanes in the Caribbean during this time period was correlated with the contemporaneous drought, as moisture was sequestered in the tropics due to El Niño and the flux in African monsoonal circulation (Webster et al., 2005; Donnelly and Woodruff, 2007; Zhang et al., 2007). The recent increase in higher intensity hurricanes (i.e. Hurricanes Floyd, 1999 and Frances, 2004) less than a decade apart, may be indicative of the influences of global climate change (Emanuel, 2005).

There are sand layers inter-bedded within the mats and allocthonous marine fauna through the record dating before 700 ybp. These sand layers are more pronounced in the cores as they become more proximal to the ocean, indicating that they came over the dune as a wash over fan morphology much like the fans mapped by Niemi et al., 2008 after Hurricane Frances. There are not any rivers on San Salvador or input into the lake basin that would bring sediment in other than that which would occur during a large storm event. There are several instances within the sandy facies (below 15 cm) where there are good correlations of sand peaks between Core A and B but do not correlate to Core D (Figures 7 - 10). This may be attributed to occasional scouring that occurs when sediment is washed in during large storm events. The dune profiles indicate that although the dune is active, sediment is not uniformly distributed throughout the basin nor is the entire basin inundated with sand, other than during large storm events.

Additionally, the sand in these layers has the same grain size, rounding and sorting as the sand found on the beach directly over the dune. This grain size is clearly identifiable in contrast with the fine-grained mud. Along with a distinct change in grain size, the sandy layers have a higher dry bulk density than that of the mats, which in contrast, have a higher water content.

The presence of marine microfossils through these arid intervals indicates marine wash over events. According to AMS radiocarbon dates, these events occurred 1000 – 3000 ybp, which falls into the period of 'hurricane hyperactivity" Liu and Fearn (1993 and 2000) described from cores taken on the Gulf Coast of the United States. The record from Storr's Lake also indicates a period of increased hurricane strikes that occurs 1000 -3000 ybp. The inability to correlate sandy peaks in Core D with Cores A and B below 20 cm supports the idea of a period of increased hurricane activity, as an increase in large storms would cause an increase in scouring more proximal to the ocean. A discontinuity in sediment accumulation during this time would also be expected with more erosional surfaces and increased deposition through wash over fans. Indeed, the rate of sediment accumulation increases from 1 cm/45 yrs for the top 15 cm to 1 cm/ 16 yrs through this time period.

Within this interval, there is a notable lack of ostracodes where there is also presence of evaporite minerals. The presence of evaporite minerals indicates arid conditions and increased evaporation in the lake basin. The lack of ostracodes in these intervals indicates that conditions may have been so extreme that even high salinity tolerant ostracodes could not survive. The possibility of the basin being open marine at this time has been negated due to the presence of these evaporites, the thin layers of marine microfauna and sand interbedded, and the lack of similarity with open marine facies identified in other Storr's Lake cores and modern Pigeon Creek.

Within the intervals containing marine microfossils, the autochthonous biota (ostracodes) within the lake basin have a documented response to these events. There is a distinct increase in ostracode abundance and community shift from C. americana to *H. setipunctata* (Figure 12). Both species have extremely high salinity and temperature tolerances and are found in the modern lake. *C. americana* prefers a muddy substrate and *H. setipunctata* prefers a sandy substrate.

The high frequency of hurricanes that pass through or near San Salvador and the other Bahamian Islands makes it important to understand the response of organisms to these disturbances. There is a distinct change in ostracode community following these storm events due to a change in substrate and increase in overall abundance due to reduction in temperature and salinity. With the influx of meteoric water, the conditions in the lake become relatively 'freshened' and create an ostracode species 'bloom.' In some instances, the conditions become fresh enough to allow for *P. bicelliforma* to appear in the community assemblage. This species however, prefers muddy substrates and does not appear to flourish even though the salinity is substantially reduced (Teeter, 1985). The *H. setipunctata* population increases at these times relative to *C. americana* and *P. bicelliforma* and is correlative across the basin in conjunction with the sand influx from storm events; indicating that these community shifts are basin-wide and not localized events. *H. setipunctata* continued to thrive in these new lake environments until the basin substrate changed from mat re-growth. The increased oxidation documented by the spectral reflectance data, occurring within the same intervals where hurricane deposits are found is a result of elevated mat productivity from the increase in meteoric water and change in substrate as a result of the storm surge. Following the oxidation there is a shift within the lake to more reducing conditions, as productivity slows due to the return to hypersaline conditions within the lake.

The spectral reflectance data indicate an increase in oxidation that occurs contemporaneously with sand layers followed by a shift back to a reducing environment. There have been previous studies documenting an increase in productivity following hurricane wash over events (Paerl et al., 2000; 2003; Yannarell et al., 2007). The changes in oxidation and reduction that are observed through spectral reflectance support these findings.

CONCLUSIONS

1. The depositional history of Storr's Lake Fortune Hill sub-basin has been very dynamic throughout its 4000 year history, recording storms as well as climate change events within its sediments.

2. The sedimentological record of Fortune Hill basin documents a change in environmental conditions from an arid to a moist climate. This change is shown by the shift from algal mat facies to sand and evaporate facies that occurs in the core transect at around 15 cm. Using the radiocarbon dates and a 1cm/45yr sedimentation rate, this change occurs at approximately 700 ybp. This is contemporaneous paleoethnobotanical data re-

covered from SSI as well as documented global Rapid Climate Change (RCC) events and historical data indicating settlement by Lucayans at this time because of fresh water availability. This study provides information about environmental conditions on SSI in the recent past that are useful to understanding the colonization and cultural history on the island.

3. The shifting environmental conditions are punctuated by hurricanes that are marked by sand layers within the cores. The sand layers often truncate one another and are texturally similar to the sand from the adjacent dune.

4. Hurricanes can be identified in the Fortune Hill sub-basin by an increase in percent sand, dry bulk density, oxidation and allocthonous marine microfossils.

5. The sedimentologic record indicates a period of hurricane hyperactivity ending around 1000 ybp and lasting at least 1000 yrs. This period of high frequency, high intensity hurricanes has been identified in other records around the Gulf Coast of North America. The presence of evaporates in these intervals indicates a closed basin and arid climate as opposed to a sandy surf environment associated with the spit accretion.

6. There is an identifiable ecological response to large storm events within the lake basin that is marked by shifting communities of ostracodes and an increase in productivity of cyanobacterial mats.

REFERENCES

Anthes, R.A., Corell, R.W., Holland, G., Hurrell, J.W., MacCracken, M.C., and Trenberth, K.E., 2006. Hurricanes and global warming – potential linkages and consequences. American Meteorological Society: 623-628.

Berman, M.J. and Pearsall, D.M., 2000. Plants, people and culture in the prehistoric central Bahamas: A view from the Three Dog Site, an early Lucayan settlement on San Salvador Island, Bahamas. Latin American Antiquity 11 (3): 219-239.

Blum, P., 1997. Reflectance spectrophometry and colorimitry. In: ODP technical notes 26 Physical Properties. 7.1-7.11

Boyle, J.F., 2001. Inorganic geochemical methods in paleolimnology. In: W.M. Last and J.P. Smol (eds.). Tracking Environmental Change Using Lake Sediments 2. Kluwer Academic Publishers: 83-143.

Coleman, J.M., 1988. Dynamic changes and processes in the Mississippi River Delta. Geological Society of America Bulletin 100: 999–1015.

Corwin, B.N., 1985. Paleoenvironmental history of Holocene ostracoda, Storr's Lake, San Salvador, Bahamas [Master's thesis]: University of Akron, 115 p.

Dakoski, A.M., and Bain, R.J., 1984. Recent Microbial Mats and Stromatolites of Granny Lake, San Salvador Island, Bahamas. In: J.W. Teeter (ed.). Proceedings of the 2nd Symposium on the Geology of the Bahamas and other Carbonate Regions: 17-26.

Davis, R.E., Hayden, B.P., Gay, D.A., Phillips, W.L., and Jones, G.V., 1997. The North Atlantic subtropical anticyclone. Journal of Climate 10: 728-744.

Delworth, T.L., Dixon, K.W., 2000. Implications of the recent trend in the Arctic/North Atlantic oscillation for the North Atlantic thermohaline circulation. Journal of Climate. 13(21): 3721-3727.

Donnelly, J.P., and Woodruff, J.D., 2007. Intense hurricane activity over the past 5,000 years controlled by El Nino and the West African moonsoon. Nature 447: 465-468.

Emanuel, K.A., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436: 686-688.

Emanuel, K.A., and Mann, M.E., 2006. Atlantic hurricane trends linked to climate change. EOS 87: 233-244.

Forester, R.M., 1990. Nonmarine calcareous microfossil sample preparation: Ostracods. USGS Technical Procedure EP-78, R1.

Gamble, D. 2008. The study of climate variability on San Salvador: Challenges and solutions to isolation. GSA Abstracts with Programs v. 40 (6), p. 416.

Gamble, D., 2010, Local-Scale analysis of the Caribbean Mid-Summer Dry Spell on San Salvador, Bahamas. 14th Proceedings Volume of the Geology of the Bahamas and Other Carbonate Regions.

Gemerdan, H.V., 1993. Microbial mats: A joint venture. Marine Geology 113: 3-25.

Intergovernmental Panel on Climate Change, 2007. Climate change 2007: Synthesis report. 73 p.

Jorgensen, B.B., Revsbech, N.P., and Cohen, Y., 1983. Photosynthesis and structure of benthic microbial mats: Microelectrode and SEM studies of four cyanobacterial communities. Limnology and Oceanography 28(6): 1075-1093.

Keim, B.D., 1997. Preliminary analysis of the temporal patterns of heavy rainfall across the Southeastern United States. Professional Geographer 49 (1): 94-104.

Kokaly, R., Despain, D.G., Clark, R.N., and Livo, K.E., 2007. Spectral analysis of absorption features for mapping vegetation cover and microbial communities in Yellowstone National Park using AVIRIS data. U.S. Geological Survey Professional Paper. 459-489.

Liu, K.B. and Fearn, M.L., 1993. Lake-sediment record of late Holocene hurricane activities from coastal Alabama. Geology 21:973-976.

Liu, K.B. and Fearn, M.L., 2000. Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in northwestern Florida from lake sediment records. Quaternary Research 54: 238-245.

Mann, J.C., and Hoffman, L.R., 1984. Algal mounds in Storr's Lake, San Salvador, Bahamas. In: J.W. Teeter (ed.). Proceedings of the 2nd Symposium on the Geology of the Bahamas and other Carbonate Regions: 41-51.

Mann, J.C., and Nelson, W.M., 1989. Microbialitic structures in Storr's Lake, San Salvador Island, Bahama Islands. PALAIOS 4 (3): 287-293.

Marchant, R., and Hooghiemstra, H., 2004. Rapid environmental change in African and South American tropics around 4000 years before present: a review. Earth-Science Reviews 66: 217-260.

McCabe, J.M. and Niemi, T.M., 2008. The 2004 Hurricane Frances deposition in Salt Pond, San Salvador, The Bahamas. In: L.E. Park and D. Freile (eds). Proceedings from the 13th Symposium on the Geology of the Bahamas and other Carbonate Regions: 25-42.

McNeese, L.R., 1988. Modern Stomatolites in hypersaline Storr's Lake, San Salvador, Bahamas [Masters Thesis]: University of North Carolina Chapel Hill.

Niemi, T.M., Thomason, J.C., McCabe, J.M., and Daehne, A., 2008. Impact of the 2004 hurricane Frances on the coastal environment of the Bahamian island of San Salvador. In: L.E. Park and D. Freile (eds). Proceedings from the 13th Symposium on the Geology of the Bahamas and other Carbonate Regions:. 43-63.

Ortiz, J.D., O'Connell, S.B., DelVisco, J., Dean, W.E., Carriquiry, J.D., Marchitto, T., Zheng, Y., and vanGeen, A., 2003. Low latitude control of marine productivity off the western margin of North America during the last 52ka? GSA abstracts with programs: 35(6): 540.

Paerl, H.W., Pinckney, J.L., and Steppe, T.F., 2000. Cyanobacterial – bacterial mat consortia: examining the functional unit of microbial survival and growth in extreme environments. Environmental Microbiology 2 (1): 11-25.

Paerl, H.W., Steppe, T.F., Buchan, K.C., and Potts, M., 2003. Hypersaline cyanobacterial mats as indicators of elevated tropical hurricane activity and associated climate change. Ambio 32: 87-90.

Park, L.E., Metzger, T., Sipahioglu, S. M., Siewers, F.D., and Leonard, K., 2008. After the hurricane hits: recovery and response to large storm events in a saline lake, San Salvador Island, Bahamas. In: L.E. Park and D. Freile (eds). Proceedings from the 13th Symposium on the Geology of the Bahamas and other Carbonate Regions: 65-76.

Park, L.E., Siewers, F.D., Metzger, T., and Sipahioglu, S.M., 2009. After the hurricane hits: Recovery and response to large storm events in a saline lake, San Salvador Island, Bahamas. Quaternary International, 195, 98-105.

Park, L.E., and Trubee, K.A., 2008. Faunal and geochemical variability of ostracode faunas from saline ponds on San Salvador Island, Bahamas. In: L.E. Park and D. Freile (eds). Proceedings from the 13th Symposium on the Geology of the Bahamas and Carbonate Regions: 11-24.

Sanger, D.B., and Teeter, J.W., 1982. The distribution of living and fossil Ostracoda and their use in the interpretation of the post-Pleistocene history of Little Lake, San Salvador Island, Bahamas. CCFL Bahamian Field Station Occasional Paper (1).

Scott, D.B., Collins, E.S., Gayes, P.T., and Wright, E., 2003. Records of prehistoric hurricane strikes on the South Carolina coast based on micropaleontological records and sedimentological evidence, with comparisons to other Atlantic Coast records. Geological Society of America 115 (9): 1027-1039.

Sellitto, V.M., Barron, V., Palumbo, G., and Colombo, C., 2007. Application of diffuse reflectance spectroscopy (DRS) to study European volcanic soils: a preliminary examination. In: Soils of Volcanic Regions in Europe. Springer Berlin Heidelberg. 437-452.

Shaklee, R.V., 1996. Weather and Climate San Salvador Island, Bahamas. The Bahamian Field Station Limited, San Salvador Bahamas: 67 p.

Teeter, J.W., 1985. Holocene lacustrine depositional history. In: H.A. Curran (ed.). Pleistocene and Holocene carbonate environments on San Salvador Island, Bahamas Geological Society of America Special Paper 300: 133-145.

Teeter, J.W. 1995. Holocene lacustrine depositional history, San Salvador Island, Bahamas. In: H.A. Curran (ed.), Pleistocene and Holocene carbonate environments on San Salvador Island, Bahamas, Geological Society of America Special Paper 300: 117-123.

Teeter, J.W., and Quick, T.J., 1990. Magnesium-salinity relation in the saline lake ostracode Cyprideis americana. Geology 18: 220-222.

Titus, R., 1984. Physical stratigraphy of San Salvador Island, Bahamas. In: J.W. Teeter (ed.). Proceedings of the 2nd Symposium of the Geology of the Bahamas: 209-228.

Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R., 2005. Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment. Science 309: 1844–1846.

Yannarell, A.C., Steppe, T.F., and Paerl, H.W., 2007. Disturbance and recovery of microbial community structure and function following Hurricane Frances. Environmental Microbiolog 9 (3): 576-583.

Zabielski, V.P., 1991. The depositional history of Storr's Lake San Salvador Island, Bahamas. [Masters thesis]: University of North Carolina Chapel Hill.

Zhang, R., Delworth, T.L., Held, I.M., 2007. Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature? Geophysical Research Letters. 34, L02709, doi:10.1029/2006GL028683.