The use of coastal lagoon sediments to track the long-term hurricane history of Jamaica, West Indies

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Abstract

Long-term data are needed to properly assess the influence of anthropogenic climate change on Atlantic hurricane frequency, however hurricane records are inconsistent prior to the development of modern monitoring techniques. Paleolimnological investigations from coastal Caribbean lagoons can be used to track changes in Atlantic hurricane activity because coastal lagoons can become inundated with seawater during hurricane events, which leaves distinct biological and geochemical signals in their sediments. This study analyzes changes in fossil diatom assemblages and chlorophyll-*a* (chl-*a*) concentrations of a ~1,500 year old sediment core from Grape Tree Pond, a coastal lagoon located in southern Jamaica. The diatom and chl-*a* profiles were used to evaluate overall changes in salinity and primary production, as well as to identify potential periods of enhanced hurricane activity. The results of this research identified three periods of pronounced hurricane activity around 1350, 1725-1785, and 1900-1925 CE, which were indicated by mixed-salinity diatom assemblages and distinct changes in chl-*a* concentrations. Additionally, two periods of drought occurring during 1650-1725 and ~1785-1900 were identified by low diatom abundance and decreased chl-*a* concentrations. These changes in the diatom assemblage and chl-*a* concentrations show that climate variability has increased following the onset of the Little Ice Age (~1450-1850 CE), however it is difficult to distinguish the impacts of recent anthropogenic climate warming on hurricane activity from those of natural Atlantic climate regimes, such as ENSO. This study is one of the first to report on the diatom species found in Jamaica, and demonstrates the potential of using fossil diatoms from coastal lagoons to track past storm activity.

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List of Common Abbreviations

1. Atlantic Multidecadal Oscillation: AMO
2. Chlorophyll-*a*: chl-*a*
3. Dissolved Oxygen: DO_2
4. El Nino-Southern Oscillation: ENSO
5. Oxygen Redox Potential: ORP
6. Sea Surface Temperature: SST
7. Total Dissolved solids: TDS

Introduction and Literature Review

Atlantic Hurricanes and Climate Change

The relationship between climate change and Atlantic hurricane activity is currently a topic of extensive research and debate (Kossin et al. 2007). Atlantic hurricanes, also referred to as tropical cyclones/storms, originate in the Atlantic warm pool, an area that encompasses the Gulf of Mexico, the Caribbean, and the Northwest Atlantic where water temperatures are greater than 28.5°C. Recent Atlantic hurricanes, such as Katrina, Sandy, and Matthew, caused devastating economic, environmental, and social impacts to coastal and island communities in the Caribbean, Central America, and eastern North America (Ferreira 2016; Wilson 2014; Petterson et al. 2006). Some research suggests that the rise in sea surface temperatures (SSTs), coupled with the increase in the frequency of intense tropical cyclones seen in recent records (the last ~35 years), is a clear indication that anthropogenic climate change is leading to an increase in major hurricane events (Goldenberg et al. 2001; Webster et al. 2005). However, this perspective has been challenged on the basis that the instrumental record is too short and unreliable to reveal trends in intense tropical hurricane activity (Landsea et al. 2006). Similarly, there are diverging opinions regarding the future influence of climate change on the frequency and intensity of hurricane activity. Some models project a decrease in hurricane frequency (Gualdi et al. 2008; Knutson et al. 2008) while others show an increase in both the frequency and intensity of tropical hurricanes, with one model projecting a doubling in the frequency of category 4 and 5 storms by the end of the 21st Century (Bender et al. 2010; Zhao et al. 2009).

Long-term Atlantic Hurricane Reconstructions

In order to properly assess the impact of recent warming on tropical hurricane frequency, long-term data extending beyond the period of anthropogenic climate change (last ~150 years) is required. Unfortunately, Atlantic hurricane research databases only extend back to 1946 for non-U.S. landfalls, and observational records prior to this year are inconsistent (Solow and Moore 2002). Paleolimnology, the scientific discipline that uses biological, chemical, and physical indicators preserved in lake sediment records to reconstruct past environmental conditions of lake ecosystems (Smol 2008), has the potential to reconstruct long-term trends in Atlantic hurricane activity. Paleolimnology has been an important field used to assess ecosystem response to various anthropogenic influences, as well as to provide baseline conditions prior to the onset of human disturbance (Smol 2008). Paleolimnological investigations are also useful to provide long-term water quality data prior to the use of modern monitoring techniques. Paleolimnological studies have provided insight into the long-term effects of environmental stressors such as acidification, eutrophication, and climate change on lake ecosystems (Smol 2008). However, in many cases, it is difficult to attribute an environmental response to one particular stressor, as multiple stressors commonly act simultaneously on ecosystems (Smol 2010). A multi-proxy approach using a variety of biological and geochemical indicators can be used for a comprehensive analysis of past ecological change and can potentially isolate the influences of individual disturbances (Smol 2010).

Preliminary paleolimnological investigations have shown promising results for the use of various proxies to reconstruct the millennia-long hurricane history of coastal/island areas of the Atlantic. The sediment cores used in these studies are retrieved almost exclusively from coastal lagoons. In general, coastal lagoons provide excellent potential to record storm-induced marine incursions because their close proximity to the ocean makes them susceptible to marine washover events (Palmer 2012). Most paleo-hurricane reconstructions have used geochemical proxies to determine incidences of marine incursion events. Liu and Fearn (2000) determined periods of intense hurricane activity along the Gulf Coast of Florida over the past 7,000 years by examining sand layers within sediment cores attributed to marine incursions during category 4 and 5 storms. Similar methods were used by Donnelly and Woodruff (2007) to isolate intervals of frequent intense hurricane strikes in Puerto Rico over the past 5,000 years. The periods of enhanced hurricane activity identified by the authors were 4800-3600, 2500-1000, 550-450, and 250 years before present (Donnelly and Woodruff 2007). One study from a coastal lagoon in Cuba used multi-proxy data including benthic foraminifera, fossil pollen, particle size analysis, and macrocharcoal influx values to assess lagoon response to sea-level fluctuations and climate change as well as infer changes in the frequency of past hurricanes (Peros et al. 2015). The particle size analysis showed periods of frequent hurricane activity which correlated with the intervals determined by Donnelly and Woodruff (2007). Lambert et al. (2007) developed a new method for reconstructing millennia-long hurricane histories by using organic geochemical proxies or organic carbon and nitrogen concentrations and their $\delta^{13}C$ and $\delta^{15}N$ compositions, which are independent of the occurrence of sand layers.

Despite some of the aforementioned studies occurring in Caribbean nations, paleolimnological investigations of coastal environments in the Caribbean are limited compared to similar investigations in higher latitudes (Peros et al. 2015; Palmer 2012). To address this discrepancy, this research aimed to reconstruct the hurricane record of Jamaica, West Indies, over the past 1,500 years. To accomplish this goal, this study employed a multi-proxy approach using fossil diatom assemblages and sedimentary chlorophyll-*a* concentrations from a dated sediment core retrieved from Grape Tree Pond, a coastal lagoon located approximately 20 km east of Kingston, Jamaica. These data were compared to geochemical data from the same sediment core that were used to reconstruct Atlantic hurricane activity (Burn and Palmer 2015) and drought events (Burn and Palmer 2014).

Caribbean Climate Dynamics

Jamaica is centrally located within the Caribbean island chain and experiences a seasonal sub-tropical maritime climate characterized by a wet season from May-October and a dry season from November-April. Annual average temperature remains constant at around 27°C and rainfall patterns are influenced by the seasonal migration of the Hadley Cell (Burn and Palmer 2014). During the summer wet season, increased solar radiation raises Caribbean and tropical Atlantic SSTs, resulting in the northward migration of the Hadley Cell creating conditions conducive to the intensification of easterly waves and the development of tropical cyclones. (Burn and Palmer 2014). Caribbean climate also varies on interannual to interdecadal timescales as a result of the Atlantic Multidecadal Oscillation (AMO) and El Niño Southern Oscillation (ENSO) events such as El Niño and La Niña. The AMO is an index of SST anomalies in the Atlantic basin that varies periodically every 60-80 years, while ENSO events occur every 2-8 years and the amplitude of these events has been shown to vary on interdecadal (50-90 year) timescales during the last millennium (Burn and Palmer 2015). The El Niño phase of ENSO results in drought conditions, while the La Niña phase leads to increased rainfall (Burn and Palmer 2014).

Diatoms as Environmental Indicators

The main biological proxy used in this research are diatom microfossils, siliceous algae belonging to the class Bacillariophyceae. Diatoms are excellent paleolimnological indicators because their frustules preserve readily in sediment, they occur in large quantities in almost all aquatic environments, and they can usually be identified to the species level (Smol and Stoermer

2010). Importantly, they are sensitive to a wide array of environmental variables and respond quickly to change due to rapid immigration and reproduction rates, which make them ideal indicators for assessing long-term trends in water quality (Smol and Stoermer 2010). Diatoms are abundant in both freshwater and marine water bodies, and different taxa have unique optima and tolerances to variables such as depth, salinity, and nutrients (Litchman et al. 2009). Therefore, there are marked differences between marine and freshwater diatom taxa, because certain species are favoured in different environmental conditions (Litchman et al. 2009). Diatoms respond so sensitively to changes in salinity that they can be classified based on their salinity (halobian) preferences (Horton et al. 2006). Species that thrive in fully marine conditions with a salinity exceeding 30 practical salinity units (psu) are referred to as polyhalobous (Horton et al. 2006). Mesohalobous diatoms exist in salt concentrations of between 0.2 and 30 psu, and oligohalobous species generally occur in salinities of less than 0.2 psu (Horton et al. 2006). Halophobous diatoms are salt intolerant and are found exclusively in fresh water (Horton et al. 2006). These categories can be further divided into oligohalobous-halophilous (prefer weakly brackish waters) and oligohalobous-indifferent (tolerant of slightly brackish conditions) (Horton et al. 2006). Diatoms can also be classified based on habit preference (planktonic, benthic, and epiphytic), and many limnological variables, most notably pH, nutrient concentrations, and temperature (Horton et al. 2006).

Prior research has examined the effects of marine incursions from tsunamis and hurricanes on diatom assemblages (Horton and Sawai 2010). While it may be assumed that marine diatom species would dominate tsunami deposits given they are transported by rapid marine washover events, in actuality diatoms in tsunami deposits are generally composed of mixed assemblages of marine, brackish, and freshwater taxa (Horton and Sawai 2010). Diatoms in tsunami deposits may also be broken due to the turbulence of the incursion (Horton and Sawai 2010). Diatoms can also be used to determine the inland extent of tsunamis. For example, in Niawaikum River (Washington State, USA), sand deposits resulting from a tsunami following an earthquake in 1700 CE extend 3 km inland from the mouth of the river, but marine diatoms are present at least 1 km farther upstream from the sand deposits, suggesting that the tsunami extended further than previously estimated (Hemphill-Haley, 1995). The results of this study illustrate that the presence of marine diatoms in inland lakes and ponds can be useful indicators of large marine incursion events.

The identification of storm-surge deposits from hurricanes is similar to tsunamis in that they both contain unusual sand deposits and show abrupt changes in diatom assemblages (Horton and Sawai 2010). For example, a hurricane mud layer in a salt-marsh pond resulting from storm-surges during Hurricane Andrew that made landfall in Louisiana on August 26, 1992 consists of diatom species from marine, brackish, estuarine, and freshwater sources (Parsons 1998). The author attributes the composite nature of the hurricane sediment to the fact that diatoms were transported and combined from a variety of sources during the storm, resulting in sediment containing higher diatom species diversity from mixed salinity environments (Parsons 1998). The study site of this project, Grape Tree Pond, is a freshwater lagoon and thus freshwater diatoms are expected to dominate. The presence of either marine and/or brackish taxa can be interpreted to be a result of marine wash-over events from hurricane activity.

Fossil Pigments

Primary production is the amount of autotrophic biomass produced within a system and is an important variable in determining overall lake tropic status. Primary producers determine the amount of energy available within an ecosystem, and changes in primary producer biomass can trigger population shifts throughout higher trophic levels. Primary production can be influenced by a number of abiotic factors, including light availability, temperature, and nutrients. Fossil pigments are commonly used to evaluate changes in lake primary production (Leavitt & Hodgson 2001). Additionally, fossil pigments can be used as indicators of algal and bacterial composition and food-web dynamics, as well as indicators for a variety of anthropogenic impacts such as eutrophication, acidification, and climate change (Leavitt and Hodgson 2001). The main sources of pigments in lakes include benthic and planktonic algal communities, phototrophic bacterial populations, and aquatic macrophytes (Leavitt and Hodgson 2001). Chlorophyll-*a* is a pigment frequently used to infer past changes in whole-lake production. Increases in sediment chl-*a* concentration has shown to track eutrophication responses in lakes of varying trophic states (Michelutti and Smol 2016; Michelutti et al. 2010). Additionally, sediment chl-*a* levels in remote Arctic lakes are speculated to have increased due to longer growing seasons caused by recent anthropogenic warming (Michelutti et al. 2005). This study used sediment chl-*a* determinations to reconstruct past primary production and infer historic trophic status changes of Grape Tree Pond.

Study Rationale

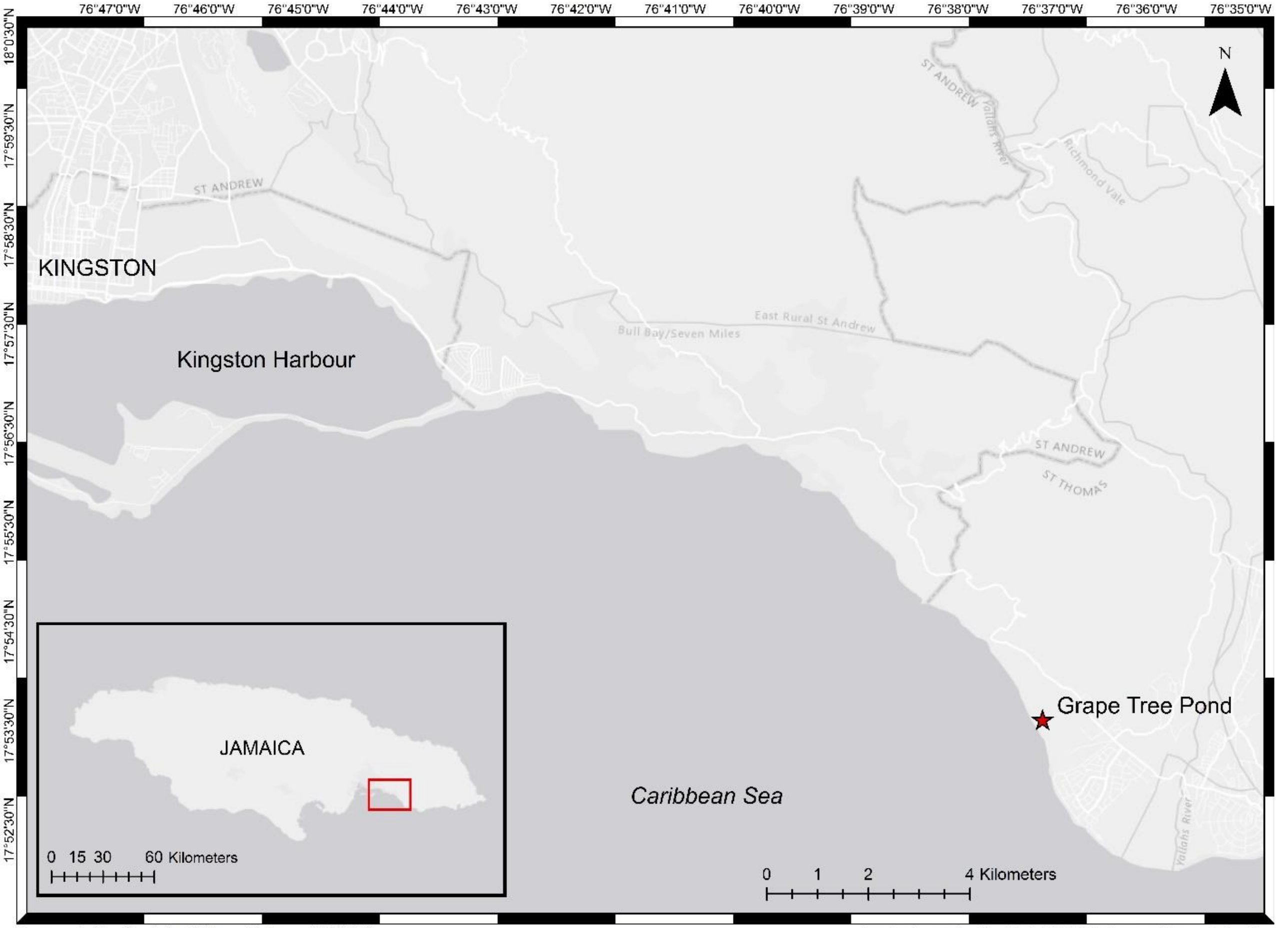
A previous paleolimnological investigation conducted by Burn and Palmer (2015) used geochemical data from sediment cores taken from Grape Tree Pond to reconstruct Atlantic hurricane activity over the last ~1,500 years. The results from their research show an increasing trend of hurricane activity within the last ~150 years, however this recent activity has not exceeded the range of natural climate variability displayed during the last millennium (Burn and Palmer 2015). My research will assess if a paleolimnological approach can be used to reconstruct the hurricane history of Jamaica by examining the temporal changes in the diatom species distribution of Grape Tree Pond over the past 1,500 years. The aims of this research are to: (1) describe the diatom assemblages of Grape Tree Pond and assess how the diatom species distribution has changed over time; and (2) use the diatom and chlorophyll-*a* record to assess salinity and production changes in Grape Tree Pond, and determine if these changes can be related to the past hurricane activity of this region.

This research is unique as relatively few studies have used diatoms as a proxy for paleo-hurricane reconstructions. Additionally, few papers have reported on the diatom assemblages from this region of the world, meaning this research will expand current scientific knowledge of diatom species distributions in Caribbean environments. This investigation will also contribute to the body of research examining the use of coastal lagoon sediments as records of hurricane activity. Due to the millennia-long time scale of the sediment record, this study may help resolve inconsistencies in the Atlantic hurricane history of the Caribbean prior to modern monitoring techniques. Finally, this research will be used to assess the relationship between anthropogenic climate change and hurricane frequency, which can have global implications for natural disaster mitigation strategies.

Methods

Site Description

Grape Tree Pond (17°53’37”N, 76°37’06”W) is a shallow (<1 m deep) freshwater-fed coastal mangrove lagoon located 20 km east of Kingston on the south coast of Jamaica (Figure 1). Grape Tree Pond is one of many shallow ponds that comprise the Albion Ponds, all of which are situated on a limestone catchment bounded by the Yallahs River alluvial fan to the east and the foothills of the Blue Mountains to the north and west (Burn and Palmer 2014). The lagoon is



Map created by Charlotte Heller on February 27, 2017
Projection: Transverse Mercator
GPS Coordinates provided by Burn and Palmer (2014)

Service Layer Credits: Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 1. Location Map of Grape Tree Pond, Jamaica. Coordinates for Grape Tree Pond from Burn and Palmer (2014).

surrounded by dense mangrove forests on all sides except the south, where there is a ~100 m beach of siliciclastic material separating the pond from the Caribbean (Burn and Palmer 2014).

Grape Tree Pond is a closed basin that receives water from precipitation, surface runoff and groundwater flow. The Pond receives most precipitation during the summer rainy season (May-October) and may experience periods of extended drought during the dry winter season (November-April) when evaporation exceeds precipitation (Burn and Palmer 2014). However, the constant groundwater flow protects the pond from drying out entirely (Burn and Palmer 2014).

Water chemistry measurements taken at the sediment-water interface were collected on July 8th, 2013 at three sites in Grape Tree Pond using a YSI 556MPS multi-parameter handheld meter (Burn and Palmer 2014). Table 1 provides the average values of each parameter based on these data. At the time of measurement, the pond was ~50 cm deep, brackish (salinity 15.9‰**)** with a pH of 8.6 indicating well-buffered conditions (Burn and Palmer 2014). High mean total dissolved solids (TDS = 17,092 mg l^{-1}) and high conductivity (29,492 µS cm^{-1}) indicate high concentrations of dissolved inorganic salts (Burn and Palmer 2014). The lagoon was also experiencing anaerobic conditions at the time of measurement as indicated by the high average water temperature (31.4°C), low average dissolved oxygen content (3.51 mg l^{-1}, O_2 saturation 51.8%) and average oxygen redox potential (ORP) of +48.00 (Burn and Palmer 2014).

Table 1. Average water chemistry measurements from the sediment-water interface (50 cm) of three sites in Grape Tree Pond taken July 8th, 2013 using a YSI 556MPS multi-parameter handheld meter. Data used for these averages first published by Burn and Palmer (2014).

Parameter	Average measurement at sediment-water interface (50 cm)
Temperature (°C)	31.4
Conductivity (µS/cm)	29,492
TDS (mg/l)	17,086
Salinity (‰)	15.95
DO_2 (mg/l)	3.51
DO_2 (% saturation)	51.8
pH	8.61
ORP (mV)	+48.00

Sample Field Collection

Three sediment cores (GT1, GT2, and GT3) were taken from Grape Tree Pond in 2011 using a Colinvaux-Vohnout drop hammer modified piston corer (Burn and Palmer 2014). GT3 was the core used in this study for chl-*a* and diatom analysis and is 217 cm in length. The core was split and sectioned at 1 cm intervals and stored in Whirl-pak® bags at 4°C until the time of processing.

Radiocarbon Dating

A sediment core chronology for Grape Tree Pond was previously produced by Burn and Palmer (2014) using five accelerator mass spectrometry ^{14}C dates ($\pm 2\sigma$) on well-preserved and identifiable terrestrial plant macrofossils from core GT1. A composite sediment record was constructed by cross-correlating the sediment stratigraphic changes of the three cores (Burn and Palmer, 2014). An age-depth model was constructed by Burn and Palmer (2014) using a smooth spline fitted through the calibrated radiocarbon dates from four of the terrestrial plant macrofossils.

Chlorophyll-a

Spectrally-inferred chlorophyll *a* concentrations were previously determined following methods provided in Michelutti et al. (2010). Briefly, freeze-dried sediments were sieved through 125 µm mesh size and transferred to glass vials. Sediment samples were analyzed spectroscopically over the range of 400 to 2500 nm using a Model 6500 series Rapid Content Analyzer (FOSS NIRSystems Inc.) Inferred chl-*a* concentrations were determined using the relationship between the peak area between 650 and 700 nm and calculated using the equation given in Michelutti et al (2010). To assess the relationship between chl-*a* concentrations and salinity, a figure displaying the relationship between inferred chl-*a* concentration (mg/g dry weight) and Chlorine (Counts^{-s}) from the years 1200 to 2000 CE was provided by Dr. Michael Burn (personal communication, March 10, 2017).

Diatom microfossil Preparation

Approximately 0.02 g of freeze-dried sediment for each 1.0 cm interval was placed in a glass vial and treated with 10% hydrochloric acid to remove carbonate material (Battarbee et al. 2001). The slurries were allowed to settle and then aspirated and diluted with distilled water.

This process was repeated until the slurries reached a pH of 7. The slurries were then treated with a solution of nitric and sulfuric acids to remove organic matter (Battarbee et al. 2001). Approximately 15 ml of the acid solution was added to each vial. The vials were then placed in an 80°C water bath for approximately two hours (Battarbee et al. 2001). After the samples settled, the acid solution was aspirated and distilled water was added. This process was repeated until a pH of 7 was reached. The sample residue was suspended in distilled water until slide preparation (Battarbee et al. 2001).

Approximately 0.2 ml of each slurry were pipetted onto cover slips, at varying dilutions, allowing the diatoms to settle and the water to evaporate (Battarbee et al. 2001). Different dilutions are necessary in order to have a manageable number of valves in the field of view. Once the coverslips were dried, they were mounted on slides using a small drop of Naphrax, a permanent mounting medium (Battarbee et al. 2001).

Diatom Counts and Scans

Diatoms were examined using light microscopy under oil immersion at 100 X objective (magnification of x1000). A minimum of ~300 diatom valves were counted at every 10 cm interval resulting in a total of 23 intervals. A count of 300-600 valves is recommended for routine analysis (Battarbee et al. 2001). Counting every 10 cm was determined to be sufficient to assess the long term water quality changes of Grape Tree Pond while also being able to be completed within the time constraints of this project. Intact frustules were counted as 2 valves and fragments consisting of more than half of a diatom were included in the counts (Battarbee et al. 2001). Valves were identified to the species level based on taxonomic guides primarily of Krammer and Lange-Bertalot (1986-1991). In rare instances where valves could not be identified to the species level, they were categorized by genus (Battarbee et al. 2001). Diatoms which resembled a particular species but could not be identified with complete certainty were labelled with that species name followed by “aff.” (affinity). In addition to the detailed diatom counts, every single interval of the sediment core was scanned for diatom taxa that may indicate marine influences. All intervals were scanned on the coverslip on which the original slurry was mounted. The number of transects scanned was representative of the number of diatom valves counted (approximately 300).

Analyses

The relative abundance of each species was calculated for each interval by dividing the number of valves of each species by the total number of valves counted and multiplying by 100. A stratigraphic profile was then created displaying species which have ≥5% abundance in at least one interval. Relative abundances and inferred chl-*a* (mg/g dry weight) were plotted against the age depth-profile created from ^{14}C ages reported by Burn and Palmer (2014). Potential hurricane events inferred from the diatom assemblage were also indicated. Changes in water quality conditions of Grape Tree Pond were assessed based on the ecology of the diatom species present at each interval as well as the changes in species distribution throughout the core.

Results

Radiocarbon Dating

^{14}C dating analysis conducted by Burn and Palmer (2014) places the basal age of the Grape Tree Pond composite sediment record at approximately 1,500 years before present. The terrestrial plant macrofossils used for ^{14}C dating occurred at 64 cm, 143 cm, 176-181 cm and 222 cm and had ages of 200, 410, 1070, and 1180 ^{14}C years before present (BP) respectively (Burn and Palmer 2014) (Table 2). The calibrated years for 200, 410, 1070, and 1180 ^{14}C years BP with the highest probability are 1729-1810, 1447-1528, 1430-1522, 936-1012, and 771-900 calendar years CE respectively (Burn and Palmer 2014). These calibrated years are the most heavily weighted in the age-depth model created by Burn and Palmer (2014) (Appendix 1).

Table 2. Depth (cm), age (14C yr BP) and calibrated years CE with corresponding probability of four terrestrial plant macrofossils from Grape Tree Pond. Table adapted from Burn and Palmer (2014).

Terrestrial Plant Macrofossil #	**Depth (cm)**	**Age (14C yr BP)**	**2σ Calibrated Yr CE**	**Probability (%)**
1	64	200	1729-1810	51.6
2	143	410	1430-1522	83
3	176-181	1070	936-1021	74
4	222	1180	771-900	86.1

Chlorophyll-a

There is an apparent inverse relationship between inferred chl-*a* concentration and Chlorine content (Figure 2). Sedimentary chl-*a* trends from GT3 show a general increase of ~0.09 mg/g dry weight from 550 CE to around 1500 CE, followed by a decrease in about 0.08 mg/g dry weight around 1750, with a final increase at the top of the core of about 0.06 mg/g dry weight (Figure 3). A notable decrease in chl-*a* occurs at ~1350, corresponding with an increase in chlorine content. Distinct peaks in chl-*a* occur ~1727 and just prior to 1900, which also correspond to decreases in chlorine content.

Diatom Analysis

A total of 37 taxa were identified throughout the sedimentary profile of Grape Tree Pond (Appendix 2). A total of 12 taxa were identified as having greater than 5% abundance in at least one interval counted (Figure 3). Species with >5% abundance included *Amphora ovalis, Amphora* sp., *Cyclotella meneghiniana, Envekadea vanlandinghamii, Fallacia subhamulata* aff., *Halamphora coffeaeformis, Mastogloia braunii* aff., *Mastogloia pseudosmithii, Navicula erifuga, Nitzschia amphibia, Nitzschia* sp., *and Nitzschia microcephala* (Figure 4).

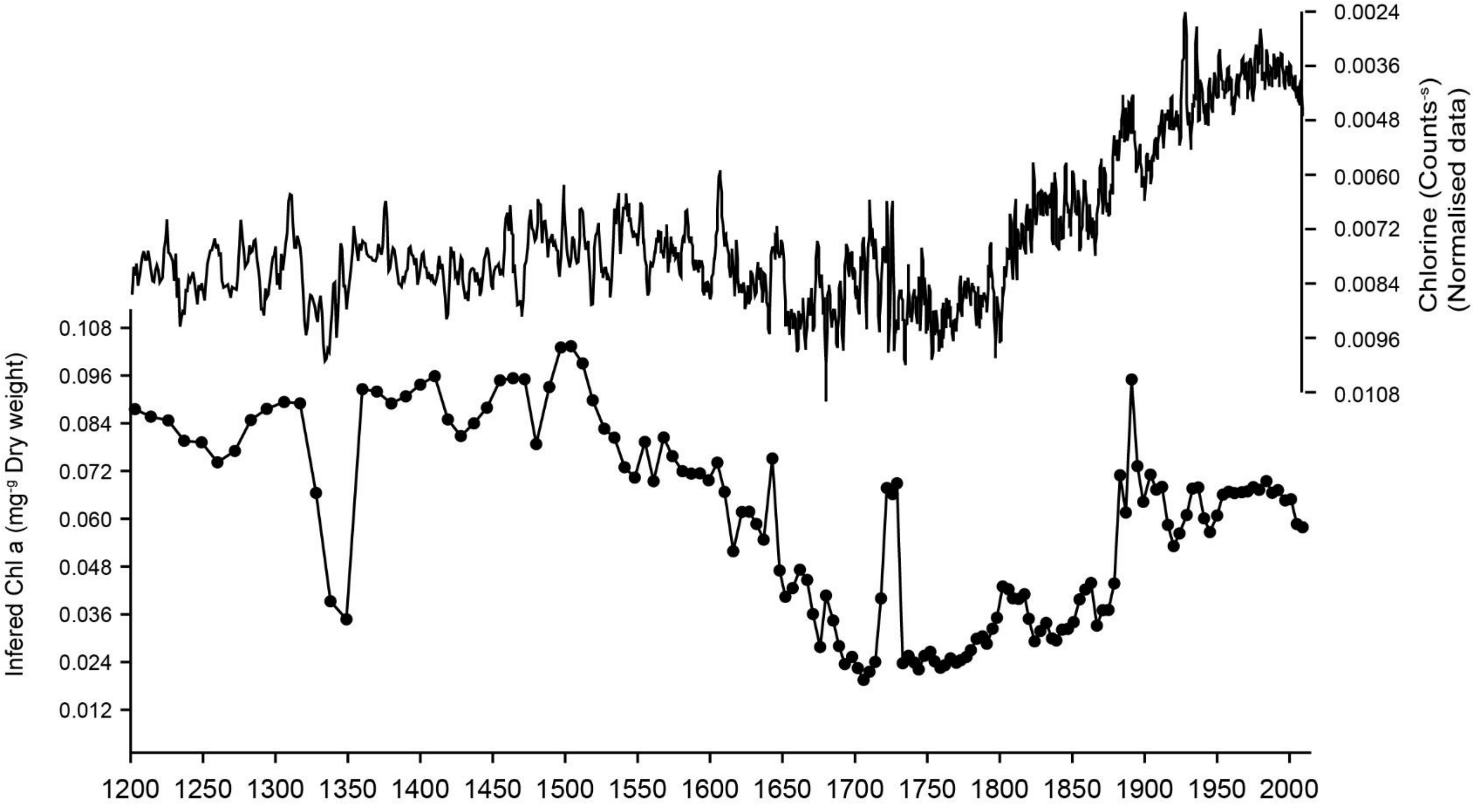


Figure 2. Inferred chlorophyll-a concentration (mg/g dry weight) and chlorine content (Counts^{-s}) of Grape Tree Pond from 1200-2000 CE. Note: chlorine scale inverted for visual purposes. Figure provided by M. Burn (personal communication, March 10, 2017).

C. meneghiniana was the most abundant diatom as it was found in every countable interval at greater than 50% relative abundance, except for around the year 1775 where it had a relative abundance of 26%. From ~1750 to ~1800, there is a decrease in abundance of *C. meneghiniana* and an increase in abundance of species such as *M. braunii, M. pseudosmithii, A. ovalis, and F. subhamulata* aff. This section of the core also has low inferred chl-*a* levels (Figure 3). From ~1650-1750, when diatoms are in low concentrations, there is decrease in chl-*a* followed by a distinct spike in chl-*a* just prior to ~1750. Similarly between ~1775-1900, chl-*a* levels are low and then start to gradually increase, followed by a distinct spike in chl-*a*, which corresponds with a low diatom abundance in that interval and then a resurgence of diatoms starting at ~1900. At ~1350 there is a notable decrease in *C. meneghiniana* and a simultaneous increase in *Amphora* sp., *F. subhamulata* aff., *H. coffeaeformis*, and *Nitzschia* sp. This change in diatom distribution coincides with a dramatic decrease in chl-*a*. From ~550 to 1200, when *C. meneghiniana* abundances are at around 70-80%, there are higher concentrations of *H. coffeaeformis, N. erifuga, and N. microcephala.* During ~1925 *C. meneghiniana* is around 70% relative abundance and there is a higher relative abundance of *N. amphibia* and *H. coffeaeformis*. *E. vanlandinghamii* abundance remains relatively steady throughout the core. Diatom abundance was very low between the years ~1650 -1750 and ~1800 -1900.

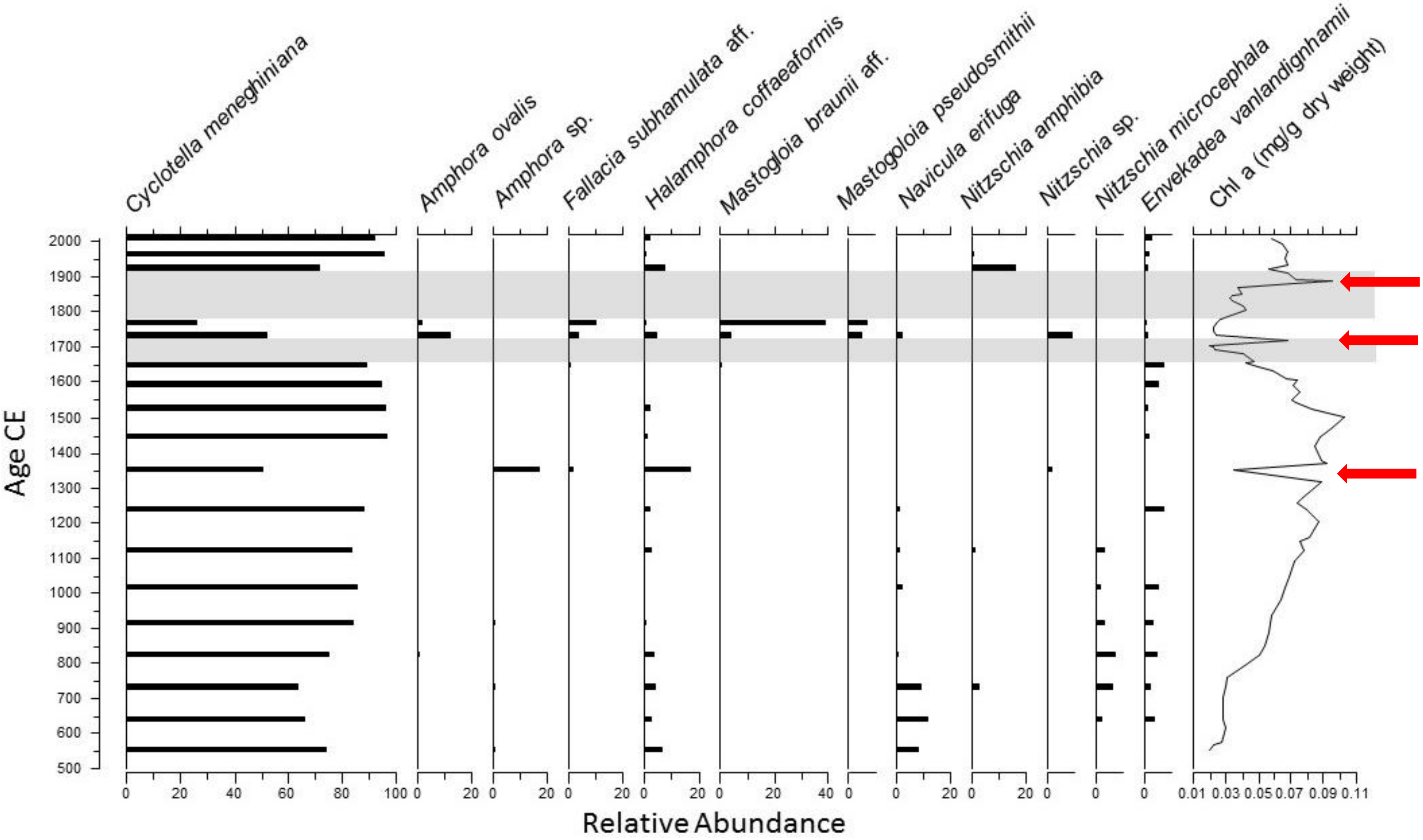


Figure 3. Stratigraphy of diatom relative abundances of major taxa (≥5% relative abundance in at least one interval) and inferred chlorophyll-*a* (mg/g dry weight) of Grape Tree Pond plotted against the corresponding age-depth profile calculated from ^{14}C analysis by Burn and Palmer (2014). Intervals of low diatom abundance are shaded light grey. Red arrows indicate potential periods of pronounced storm events determined from the diatom assemblage and chl-*a* profile.

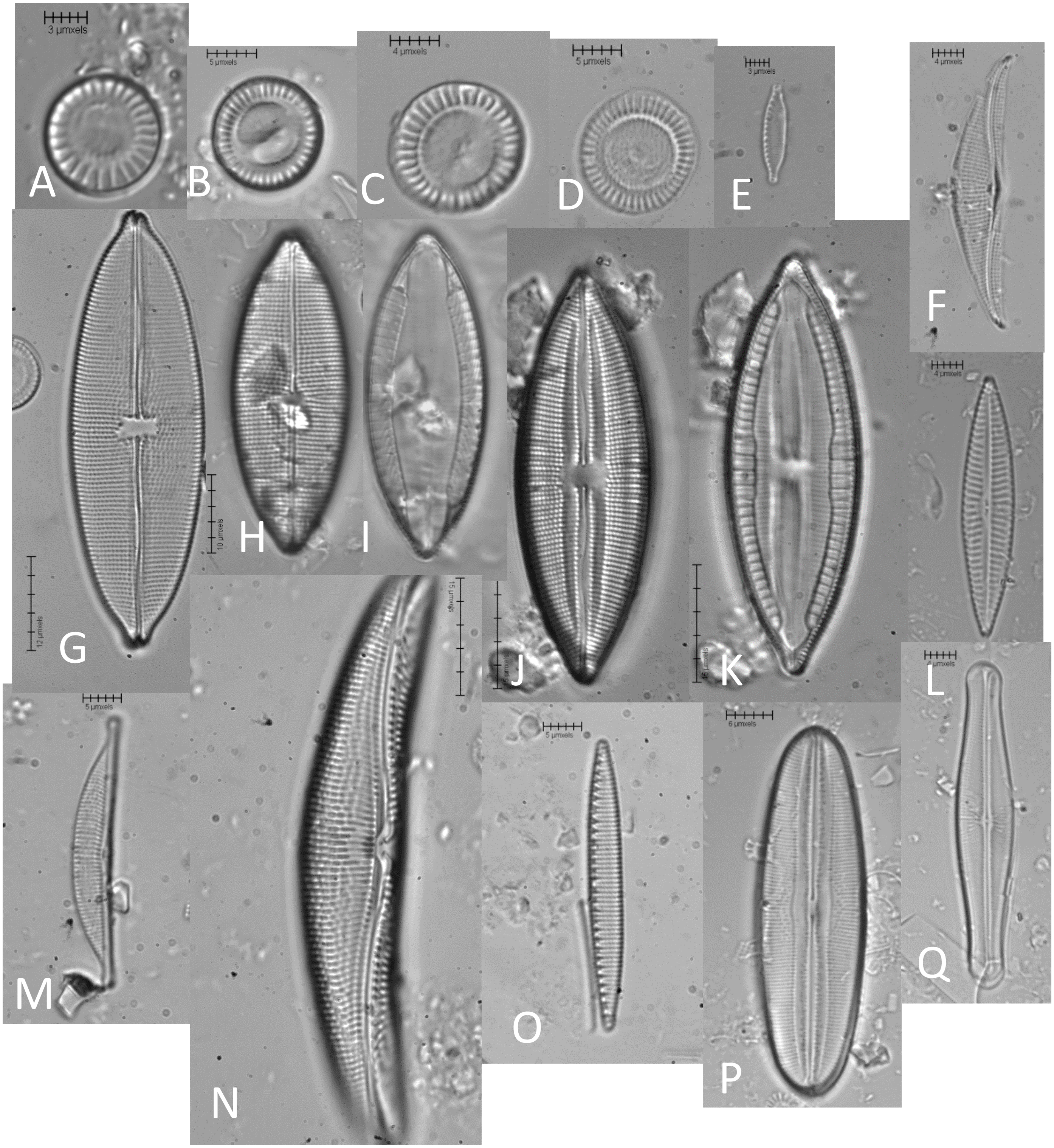


Figure 4. Common diatom taxa (≥5% abundance in Grape Tree Pond. Scale indicated on each individual image. *Cyclotella meneghiniana* (A-D); *Nitzschia microcephala* (E); *Amphora* sp. (F); *Mastogloia pseudosmithii* (G-I); *Mastogloia braunii* (J-K); *Navicula erifuga* (L); *Halamphora coffeaeformis* (M); *Amphora ovalis* (N); *Nitzschia amphibia* (O); *Fallacia subhamulata* aff. (P); *Envekadea vanlandinghamii* (Q).

Discussion

Overall, the diatom stratigraphy indicates that Grape Tree Pond has been historically brackish with elevated nutrient levels, which is consistent with modern-day water chemistry data (Burn and Palmer 2014). Grape Tree Pond contains planktonic, benthic, and epiphytic diatom species with salinity preferences ranging from oligohalobous-halophilous/oligohalobous indifferent to mesohalobous/polyhalobous. All of the species present in Grape Tree Pond are capable of thriving in eutrophic conditions (Lee et al. 2014; Wachnicka et al. 2010; Hassan et al 2009; Essien et al. 2008). The dominant taxon, *C. meneghiniana*, is considered to be a freshwater to brackish planktonic species with a salinity optimum of 0.68 g l^{-1} and a range of 0.10-4.54 g l^{-1} (Lange and Tiffany, 2002; Cumming et al. 1995). The species with the lowest salinity tolerances are *Navicula erifuga* and *Nitzschia microcephala*, which are oligohalobous halophilous, and *N. amphibia* which is oligohalobous indifferent (Hassan et al 2009). *A. ovalis* has been found in freshwater Arctic environments as well as a tropical mangrove estuary, suggesting that it has broad temperature and salinity tolerances (Hadley et al. 2010; Essien et al. 2008). *F. subhamulata* has shown to have a positive association with increasing salinity (Schroder et al. 2015). *M. pseudosmithii*, which until relatively recently was often misidentified as *Mastogloia smithii*, has only been found in coastal marshes of Florida and Jamaica as well as some inland areas (Lee et al. 2014). These costal marshes are typically brackish, slightly acidic with high conductivity and elevated phosphorous levels (Lee et al. 2014). Lee et al. (2014), who first distinguished *M. pseudosmithii* as a distinct species, determined the average optima for depth, pH, conductivity, and total phosphorous of to be 41 cm, 6.7, 2500 µS cm^{-1}, and 480 µg g^{-1} respectively.

Species considered to be tolerant of hypersaline conditions and commonly found in brackish waters include *H. coffeaeformis*, *M. braunii*, *and E. vanlandinghamii* (Sylvestre et al. 2001; Wachnicka et al. 2010; Zalat and Al-Wosabi, 2011). *H. coffeaeformis* is a widespread benthic euryhaline species which is especially common in brackish to highly saline environments in subtropical and tropical localities (Sylvestre et al. 2001). *H. coffeaeformis* populations in British Columbia lakes were determined to have a salinity optimum of 9.9 g l^{-1} and a salinity range of 1.32-74.13 g l^{-1} (Cumming et al. 1995). *H. coffeaeformis* has even been able to exist in hypersaline experimental ponds with salinities of up to 150-180% (Sylvestre et al. 2001). *M. braunii* is frequently a marine species common in brackish waters (Sabanci 2012; Zalat and Al-Wosabi 2011). In one instance it was found in a shallow coastal lagoon in Turkey located northwest of the Gulf of Izmir with a salinity between 35 and 54‰ (Sabanci 2012). *E. vanlandinghamii* is considered a marine species which has been reported from coastal waters throughout the world (Gilgora et al. 2009). This species was found in the Salton Sea, a nutrient rich, highly saline lake located in California with a salinity of 43 g l^{-1}, a temperature range of 12-40°C (Lange and Tiffany 2002). *C. meneghiniana* was also present in this lake (Lange and Tiffany 2002). *H. coffeaeformis, M. braunii,* and *C. meneghiniana* were all present in brackish streams from Scotra Island located in the northwest Indian Ocean (Zalat and Al-Wosabi, 2011). *E. vanlandinghamii* and *H. coffeaeformis* were also found in a coastal hypersaline lagoon (mean salinity 52%) from Rio de Janeiro, Brazil (Sylvestre et al. 2001). *E. vanlandinghamii* and *M. braunii* are considered to be indicator species of brackish, turbid, and nutrient rich coastal mangrove lagoon conditions in South Florida (Wachnicka et al. 2010). Small *Cyclotella* species, including *C. meneghiniana,* also dominate these mangrove lagoons (Wachnicka et al. 2010).

Coastal mangrove lagoons can act as a buffer between coastal marine and inland freshwater environments, and as a result often contain mixed diatom assemblages of freshwater, brackish, and marine species (Wachnicka et al. 2010). These mixed assemblages can increase in the wet season as a result of increased precipitation, inland freshwater flooding, and other storm influences, such as marine incursions (Wachnicka et al. 2010). Given that abrupt changes in diatom diversity resulting in mixed assemblages containing brackish, freshwater, and marine diatom species can be an indicator of hurricane events (Horton and Sawai 2010), the diatom stratigraphy from this analysis suggests that periods of more frequent hurricane activity occurred around 1350, 1750-1785, and ~1925 CE based on Burn and Palmer's (2014) age-depth model for Grape Tree Pond. These intervals contain diatom species with salinity preferences ranging from freshwater to brackish (e.g. *C. meneghiniana, N. erifuga, N. microcephala, N. amphibia, A. ovalis*), and brackish to hypersaline (e.g. *E. vanlandinghamii, H. coffeaeformis, M. braunii).*

Hurricane events are often recorded in the sediment record of coastal lagoons by sand deposit layers resulting from marine inputs (Donnelly and Woodruff 2007). In this case, there are no marine sand deposits preserved in the sediments corresponding to the intervals where mixed diatom assemblages are present (Burn and Palmer 2014). While marine sand deposit layers can further clarify intervals of hurricane washover events, their absence does not necessarily indicate the absence of hurricanes (Parsons 1998). Diatoms can identify storm surge sediment where lithostratigraphic characteristics are inadequate, and therefore do not necessarily have to be coupled with sand deposit layers (Hemphill-Haley 1995; Parsons, 1998). In addition to changes in salinity tolerances, shifts in diatom substrate preferences can also indicate hurricane events (Parsons 1998). For example, Hurricane Andrew appeared to cause a shift in diatom species towards epiphytic species related to the increase in aquatic plants as a result of geochemical changes in the sediments following landfall (Parsons 1998). From ~1350, ~1750-1800, and ~1925 CE, there is a decrease in the population of the pelagic species *C. meneghiniana* and an increase in epiphytic species such as *H. coffeaeformis, N. amphibia, M. braunii,* and *A. ovalis.* (Lange and Tiffany 2002; Zalat and Al-Wosabi, 2011; Lopez-Fuerte et al. 2013; Caglar and Pala 2016). Should hurricanes result in a shift towards epiphytic species, the presence of these epiphytic diatoms at the select intervals may further indicate increased hurricane activity during these periods. However, the presence of epiphytic species may also be due to the encroaching mangrove population as their roots can act as a substrate (Chen et al. 2010).

There is no obvious reason for the low diatom abundance from ~1650-1725 and ~1785-1900, as diatom abundance is dependent on many limnological factors. Poor diatom preservation has been previously implicated for periods of low abundance in a tropical saline lake (Flower and Ryves 2009). Valve dissolution depends upon a variety of biological factors including valve morphology and silicification, as well as environmental conditions such as sediment burial time and water quality (Flower et al. 2006). High water temperatures and pH can lead to poor valve preservation (Flower 1993; Flower et al. 2006). For example, *C. meneghiniana* populations were eliminated from sediment layers in an experimental treatment after 2 hours of alkali exposure (Flower et al. 2006). Therefore, potential increases in temperature and/or pH during these periods may explain the low diatom abundance. Additionally, abundance minima have been associated with elevated sedimentary carbonates and lake desiccation (Flower and Ryves 2009). Periods of drought in Grape Tree Pond resulted in increases in pH and the supersaturation of dissolved carbonates (Burn and Palmer 2014). As lake desiccation, high pH, and sediment carbonates are all associated with poor diatom preservation, the periods of low diatom abundance may be the result of extended drought conditions in Grape Tree Pond. These intervals correspond to drought analysis conducted by Burn and Palmer, who determined that periods of pronounced drought occurred between 1650-1720, 1780-1800, and 1840-1910. Therefore, intensive drought conditions creating unfavorable water conditions may be a possible explanation for the low diatom abundance occurring during these periods.

Changes in salinity recorded in the diatom stratigraphy are potentially corroborated by interesting changes in the sediment chl-*a* and chlorine content profile from ~1200-2000 CE. Chlorine concentration is an indicator for salinity (Liu et al 2016), therefore fluctuations in chlorine content can reflect changes in salinity. The increase in chlorine content, decrease in chl-*a*, and mixed-salinity diatom assemblage, which occurs around 1350, may indicate a hurricane incursion event. Chlorophyll concentrations tend to decrease with increasing salinity over 15 psu (Hakanson and Eklund 2010). Therefore, decreases in the inferred chl-*a* concentration coupled with an increase in salinity in coastal lagoons may be the result of marine inputs. For example, the chl-*a* concentration of a coastal lagoon decreased following the inflow of seawater into the lagoon as a result of a sandbar opening (Santangelo et al. 2007). Other studies have attributed decreases in chl-*a* concentrations immediately following typhoons within coastal aquatic environments to increased dilution from precipitation, ocean inputs, and freshwater runoff (Gang et al. 2009). Therefore, the mixed diatom assemblage, increased chlorine content, and lower chl-*a* levels present at ~1350 support evidence for a series of hurricane events which led to the inundation of Grape Tree Pond with saltwater.

Mixed diatom assemblages also occur between ~1750-1785 and around 1925. These assemblages occur just after a distinct spike in chl-*a* corresponding with an abrupt decrease in chlorine recorded around 1725 and just prior to ~1900. It can be speculated that these spikes indicate hurricane events which followed the extended periods of drought recorded in the diatom assemblage from 1650-1725 and ~1785-1900 and in Burn and Palmer's (2014) drought reconstruction. If Grape Tree pond reached hypersaline conditions during the periods of drought, a sudden storm event resulting in increased precipitation and flooding may lead to a dramatic increase in productivity, decreased salinity, and greater abundances of less saline tolerant diatoms. Abrupt spikes in chl-*a* levels and reductions in salinity have been recorded in sub-tropical lakes in response to hurricanes, followed by a return to pre-disturbance conditions within one year (Briceno and Boyer 2010). Therefore, the peak in chl-*a* and decrease in chlorine seen around 1725 and just prior to 1900 may be attributed to a sequence of hurricane events. It appears that soon after these events, the lagoon returned to pre-disturbance conditions, however the decades following this pronounced hurricane period experience a gradual increase in chl-*a* and decrease in chlorine content. This trend suggests that an enhanced period of hurricane activity may have had residual effects on the salinity and productivity of Grape Tree Pond, and allowed for the lake to recover from previous drought. The resurgence of diatoms following these spikes in chl-*a* suggests that these storms lead the reestablishment of diatom communities which were reduced during drought periods. These communities have mixed salinity preferences, likely due to the fact that the salinity of the pond was increased during the drought to levels conducive to hypersaline-tolerant species, but the freshwater storm input introduced less-saline tolerant species.

The elevated salinity tolerances of the diatom taxa present in Grape Tree Pond indicate that the lagoon has been historically brackish despite being freshwater fed and situated within a closed basin. This suggests that Grape Tree Pond has had some sort of marine influence, which may be the result of sea level change or periodic washover events. It is unlikely that historic sea level elevation is the cause of the salinity increase, as the diatom stratigraphy would show a gradual shift from brackish/hypersaline species to freshwater species as the saline water was replaced by freshwater inputs (Garcia-Rodriguez, 2006). One possible explanation for the steady presence of brackish to hypersaline-tolerant species throughout the entire core is that Grape Tree Pond has been influenced by regular marine incursions likely due to hurricane activity. Additionally, the periods of low diatom abundance and the corresponding geochemical analysis (Burn and Palmer 2014) indicate that Grape Tree Pond has also had regular influences of drought, which may also contribute to elevated salinity levels. It is difficult to assess whether the presence of less-saline tolerant species at the bottom of the core is the result of hurricane activity, or if this reflects that Grape Tree Pond had a lower salinity at this point in time. If this were the case, the reduction in the abundance of these oligohalobous halophilous/oligohalobous indifferent species would indicate that the salinity of the pond has increased over the past 1,500 years. Therefore, the historically elevated salinity level of Grape Tree Pond could be the result of accumulated marine inputs from hurricane activity, coupled with salinity increases resulting from regular drought events.

The diatom stratigraphy and chl-*a* profile indicate a period of higher climate variability starting in ~1350. This trend is especially evident from ~1650 to 1950, where fluctuations in diatom abundance and chl-*a* levels suggest an alternating pattern of pronounced drought followed by periods of high storm activity. The hurricane analysis conducted by Burn and Palmer (2015) determined that hurricane activity was subdued during the Medieval Climate Anomaly (MCA) (~900-1350 CE) and became more produced during the Little Ice Age (LIA) (~1450-1850 CE), followed by a period of variability occurred between ~1850 and ~1900 before entering another subdued state during the industrial period (~1950-2000 CE). In general, the results of this study corroborate these findings, as potential evidence of hurricane activity is only tracked in the diatom record and chl-*a* profile following 1350. These results also correspond with those of Donnelly and Woodruff (2007), who determined that a period of enhanced hurricane activity has occurred within the past 250 years. Additionally, while hurricane activity was greater during the LIA, it also had more frequent periods of drought compared to the MCA (Burn and Palmer 2014), suggesting that climate fluctuations were more pronounced in the LIA compared to the MCA. The changes in the diatom distribution and fluctuations in chl-*a* recorded in this study starting around 1350 also indicate that variations in climate have become more distinct during the LIA and from ~1850-1900.

It is difficult to assess changes in the trophic status of Grape Tree Pond from the diatom assemblage given the consistent dominance of *C. meneghiniana* and other eutrophic species (Lee et al. 2014; Wachnicka et al. 2010; Hassan et al 2009; Essien et al. 2008). The stable presence of eutrophic taxa is likely the result of constant inputs of high quality organic matter from mangrove litter fall (Ake-Castillo and Vasquez, 2008). The variability of the chl-*a* profile indicates no consistent monotonic trend in lake productivity, although there appears to be a general increase in chl-*a* concentration over time. However, given that chl-*a* levels were the highest during periods prior the industrial era (~1400-1500) it cannot be assumed that the recent increase is a result of anthropogenic activity rather than natural variability. Given the remote location of the lagoon and its highly vegetated perimeter, it is unlikely it has experienced eutrophication from anthropogenic inputs. While chl-*a* data has been used to infer changes in production as a result of human activity (Michelutti et al. 2010; Michelutti and Smol 2016) and climate change (Michelutti et al. 2005) in other lakes, it is difficult to ascertain the influences of these forces from the profile of Grape Tree Pond. This is most likely due to the interannual and interdecadal variations in climate in the Caribbean region as a result of climate regimes such as the AMO and ENSO. The periodical fluctuations in precipitation levels and temperature resulting from these events, coupled with the constant input of nutrients from litter fall, may make it difficult to distinguish anthropogenic influences from natural climate variability on lake trophic status using the chl-*a* and diatom profiles of tropical mangrove lakes.

The results of this study indicate that diatoms are effective indicators at assessing long-term changes in salinity in coastal tropical environments. This research also demonstrated that diatoms and sediment chl-*a* can be useful indicators of historic trends in climate variability which can complement results from geochemical analyses. The findings of this study also supported current research which shows that coastal lagoons are excellent records of historic hurricane activity. While counting every 10 cm was deemed to be sufficient in determining the long-term salinity changes of Grape Tree Pond over the past ~1,500 years, it is recommended that diatom analysis be conducted on more frequent intervals to determine the effects of periodical changes in climate resulting from AMO and ENSO. The resolution of this diatom analysis was coarser compared to Burn and Palmer's (2014) geochemical analysis, therefore some periods of climate variability have likely been missed. Additionally, this analysis was limited to only two biological indicators. In order to distinguish the effects of multiple stressors on the salinity and productivity of Grape Tree Pond, further investigation using other paleoindicators should be conducted. Another limitation of this study is the underrepresentation of tropical coastal environments in paleolimnological research compared to temperate environments. Specifically, reports on the diatom communities of Caribbean and Jamaican lakes are generally lacking, which made it difficult to identify some of the species present in Grape

Tree Pond with certainty. This study is one of the first papers to report on diatom assemblages from Jamaica, and therefore can be a point of reference for further research investigating the diatom assemblages of coastal Caribbean environments. While this study shows promising results for the use of diatoms and chl-*a* as paleoindicators for climate-related salinity and primary production changes in Caribbean environments, more research must be conducted to further scientific understanding of the long-term influence of Atlantic climate regimes on coastal lagoons in tropical environments.

Summary

1. The diatom assemblage of Grape Tree Pond contains benthic, planktonic and epiphytic taxa indicative of eutrophic conditions and salinity preferences ranging from oligohalobous-halophilous/oligohalobous indifferent to mesohalobous/polyhalobous. The most abundant taxon, dominated by *C. meneghiniana*, indicates that Grape Tree Pond has been historically brackish with elevated nutrient levels.
2. The fossil diatom and sediment chl-*a* profile indicate three potential enhanced periods of storm activity which occurred around 1350, 1725 and just prior to 1900. The event(s) during 1350 are indicated by a mixed-salinity diatom assemblage and a distinct decrease in chl-*a*. The events around 1725 and 1900 are indicated by spikes in chl-*a* and a reestablishment of a mixed-salinity diatom community following periods of low diatom abundance.
3. Two periods of low diatom abundance occur between 1650-1725 and ~1785-1900, which are speculated to indicate periods of pronounced drought. These time intervals correspond to the periods of extended drought conditions determined from the geochemical analysis from Grape Tree Pond conducted by Burn and Palmer (2014) which occurred from ~1650-1720, ~1780-1800, and ~1840-1910.
4. In general, the results of this study support previous research (Burn and Palmer 2015) which indicates that climate variability and hurricane activity was higher during the LIA compared to the MCA, and that fluctuations in climate continued between ~1850 and 1900.
5. Given the strong influences of interannual and interdecadal Atlantic climate regimes such as the AMO and ENSO on Caribbean coastal environments, it is difficult to distinguish

the influence of anthropogenic climate warming from natural climate variability in the sediment record of Grape Tree Pond.

6. The results of this study show promise for the use of diatoms and chl-*a* as indicators for historic climate trends in coastal Caribbean environments, however more multi-proxy paleolimnological research is needed in order to further scientific understanding of the historic relationships between salinity, productivity, and climate in tropical costal lagoons.

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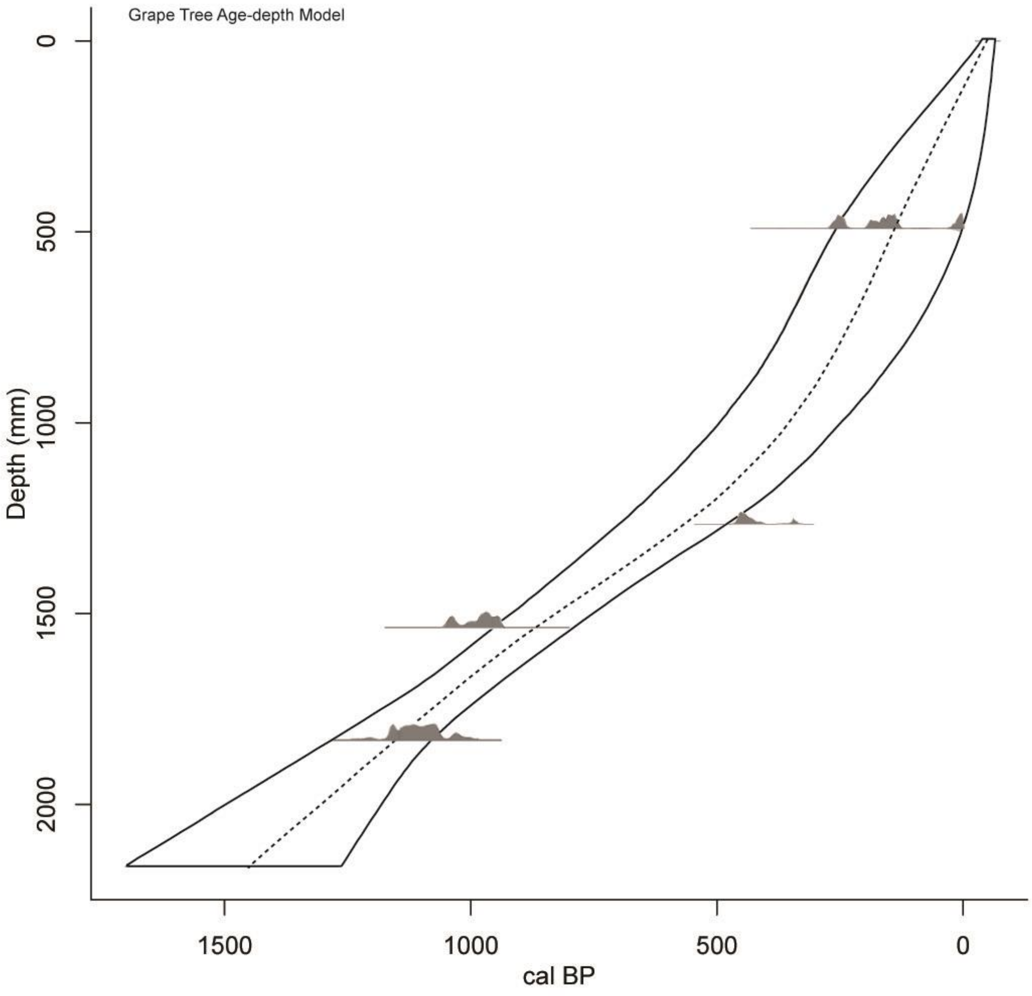
Appendices

Appendix 1. Age-depth model for Grape Tree Pond sediment record created by Burn and Palmer (2014). Constructed using a smooth spline fitted through four calibrated 14C dates on well-preserved and identifiable terrestrial plant macrofossils. Dates reported in calibrated calendar years CE (2σ error ranges).



Appendix 2. Grape Tree Pond diatom taxa raw counts. Diatoms which could only identified to the genus level indicated by the genus name followed by “sp.” (species). Diatoms which resembled a certain species but could not be identified with complete certainty indicated with species name followed by “aff.” (affinity).

Depth (cm)	***Achnanthes exigua***	***Achnanthes minutissima***	***Achnanthes* sp.**	***Amphora ovalis***	***Amphora* sp.**	***Anomoeoneis sphaerophora***	***Campylodiscus. Hibernicus* aff**	***Cyclotella meneghiniana***	***Diploneis oblongella***
0-1								321	
10-11								410	
20-21				2				293	
30-31									
40-41									
50-51									
60-61	3			7		1		80	
70-71	2			48				196	
80-81									
90-91	4							312	
100-101								332	
110-111								268	
120-121								287	
130-131	2				50			148	
140-141	2							322	
150-151	8			2				242	2
160-161	6		6			2		600	
170-171					4			270	
180-181	2	4		4				382	
190-191	5			2	6	1	2	305	
200-201	8					2	2	190	
210-211					4		6	242	
216-217									

Depth (cm)	***Cymbella celiciacum***	***Cymbella celiciacum***	***Envekadea vanlandignhamii***	***Fallacia pygmaea***	***Fallacia subhamulata* aff.**	***Fragilaria* sp.**	***Gomphonema insigne***	***Gomphonema minutum***	***Gyrosigma attenuatum***	***Halamphora coffeaeformis***
0-1			11				2			8
10-11			8							4
20-21			6				2			32
30-31										
40-41										
50-51										
60-61	2	2	4		32		1			2
70-71			6		14	2				17
80-81										
90-91			26		4					
100-101			18							
110-111			4							6
120-121			6							4
130-131					6		2			50
140-141			26							8
150-151			2				6			7
160-161			36				8			
170-171			11	4	2		4			4
180-181			25	2			4			18
190-191			13	1	2		2	2		20
200-201			12	4						8
210-211			2	2			1		4	23
216-217										

Depth (cm)	***Mastogloia braunii*** **aff.**	***Mastogoloia pseudosmithii***	***Navicula*** **sp.**	***Navicula descripta***	***Navicula erifuga***	***Navicula erifuga.***	***Navicula explanata***	***Navicula falaisensis***	***Navicula trivalis***	***Navicula phyllepta***	***Nitzschia amphibia***
0-1					2						2
10-11											4
20-21					2						67
30-31											
40-41											
50-51											
60-61	120	23								23	
70-71	15	22	4		10					2	
80-81											
90-91	2										
100-101											
110-111											
120-121											
130-131						6					
140-141					6						
150-151					4						4
160-161		2		2	20	2					2
170-171		2	2		2						
180-181		2		2	6	7		4			2
190-191			20	7	44		1				14
200-201				2	34			4	6	2	2
210-211					28	8					
216-217											

Depth (cm)	***Nitzschia* sp.**	***Nitzschia inconspigua***	***Nitzschia microcephala***	***Nitzschia palea***	***Nitzschia pura***	***Pinnularia* sp.**	***Reimena sinuata***	***Surirella* sp.**	**Total**
0-1									346
10-11		2							428
20-21		2						2	408
30-31									0
40-41									0
50-51									0
60-61			2			4	1		305
70-71	36								374
80-81									0
90-91									348
100-101									350
110-111									278
120-121									297
130-131	6			4	18				292
140-141									364
150-151			10						287
160-161			16						702
170-171			12					2	319
180-181		2	38						504
190-191			29						476
200-201			8						284
210-211			2				2		324
216-217									