# A long-term perspective of climate change in the Caribbean and its impacts on the island of Barbuda

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## Abstract

Small Island Developing States (SIDS) of the Caribbean are vulnerable to the effects of climatic change. The damaging impacts of contemporary sea-level rise and changing rainfall patterns are clear and have had a significant influence on Barbuda's physical, economic and socio-cultural landscapes. In 2017 Hurricane Irma made landfall in Barbuda as a major category 5 hurricane, which led to widespread devastation and the evacuation of the island's entire population. The passage of this large storm is consistent with a recent increase in Atlantic hurricane activity; however, the attribution of individual catastrophic events to climate change, whether natural or anthropogenic, remains a scientific challenge. Nevertheless, the lasting impacts of Hurricane Irma in Barbuda emphasises the vulnerability of SIDS to regional- and global-scale climatic phenomena. In this chapter, we show how climate has changed in the Caribbean over different spatial and temporal scales and how varying natural and anthropogenic factors have shaped Barbuda's climatic history. We highlight projections of 21st century climate change for the Caribbean region and its likely impacts on Barbuda's coastal ecosystems, potable groundwater resources and natural heritage.

## 1. Introduction

On the 6th September 2017, Hurricane Irma devastated the island of Barbuda making landfall as a category 5 hurricane at 0545 UTC with catastrophic maximum sustained winds of 178 miles per hour (155 kt) and a minimum pressure of 914 mb (Cangialosi et al. 2018). It went on to cause widespread devastation across the Caribbean and the United States becoming one of the strongest and costliest hurricanes on record in the tropical Atlantic. A tide gauge on Barbuda recorded a peak water level of 2.4 m Mean Higher High Water indicating a storm surge of at least 2.4 m above ground level for parts of the island. 95% of structures and homes were either damaged or destroyed including the island's airport and the water supply and communications were completely cut off. The subsequent threat of Hurricane Jose meant that the entire island was evacuated to Antigua leaving Barbuda abandoned and uninhabited for the first time in its long and complex settlement history. At the time of writing (January 2021), schools and several shops have reopened and about half of the inhabitants have returned and the fishing season is being revived; however, the legacy of Hurricane Irma will continue to affect the inhabitants of Barbuda for some time to come.

The physical and socio-cultural devastation that hurricane Irma left in its wake emphasises the fragile reciprocal relationships between human settlement on Small Island Developing States (SIDS) and climatic change. It also encourages the inquisitive mind to ponder not only the extent to which island settlement or abandonment was influenced by natural climate variability in the past, but also how anthropogenic climate change may impact society towards the latter half of the 21st Century and beyond. In this chapter, we review how climate has changed in Barbuda on different temporal and spatial scales and emphasise the complex network of global and regional forcing factors, both natural and anthropogenic, that make the climate of the island what it is today. It is impossible to understand the past, present and future climate of Barbuda without placing it in the broader context of regional (Caribbean-wide) and global climate variability. Thus, our discussions also include comprehensive analyses of climate dynamics on different spatial scales.

Barbuda is a small (161 km$^2$), low-lying limestone island of the Lesser Antilles island arc (Figure 1), which separates the tropical Atlantic Ocean from the Caribbean Sea (Brasier and Donahue 1985). Barbuda's maximum average elevation of ~38 m corresponds to a massive limestone plateau of Pliocene age known as 'The Highlands', which occupies the southeast segment of the Island. The plateau is bounded by abandoned sea cliffs to the north and east and by alternating late-Pleistocene consolidated beach ridge and lagoon deposits to the west and south, which form the Codrington Limestone Group (Martin-Kaye, 1959). The majority of Barbuda's inhabitants live in the village of Codrington located to east of the island adjacent to Codrington Lagoon, a semi-enclosed coastal lagoon. Mangrove forests surround the island and are home to second largest frigate bird colony in the region. A rare inland mangrove forest comprising extensive stands of *Rhizophora mangle* (red mangrove) fringes Freshwater Pond, one of just a few sources of fresh-brackish water on the island. This mangrove ecosystem may be a relic of a more extensive forest that was connected previously to the Caribbean Sea (Stoddart et al. 1973). Fringing coral reefs surround the island in several locations, particularly to the south in White Bay. The island's limestone geology is porous and supports a network of wells across the island, which feed into shallow aquifers with varying ranges of brackish water. These wells were important historically for several purposes including cattle ranching, agriculture, washing and drinking. Today they are used less, but are still important for watering domestic and wild animals, construction activities and as sources of potable water for hunters (Boger et al. 2014).

## 2. Contemporary climate dynamics of the Caribbean

The climate of the Caribbean is characterised by a seasonal subtropical maritime climate with average temperatures of around 27°C and a minimum/maximum temperature range of 17–35°C, which remains fairly consistent across the region. The annual precipitation cycle exhibits greater spatial variability than temperature but may be generalized broadly by a dry season from December to April and a wet season from June to November (Gamble and Curtis 2008; Taylor 2002; Curtis 2013). Precipitation is controlled by the interplay between thermodynamic processes associated with Sea Surface Temperature (SST) variability and dynamic processes associated with regional wind shear. These vary in response to the seasonal and interannual migration of the Intertropical Convergence Zone (ITCZ) and associated changes in the North Atlantic Subtropical High (NAH) and the intensity of the Caribbean Low-Level Jet (CLLJ) (Wang 2007; Cook and Vizy 2010; Moron et al. 2016; Figure 2), a regional extension of the northeast trade winds. In general, the seasonal rainfall pattern is bimodal, though it exhibits considerable variability across the region. Bimodality is manifested by an early and a late rainfall peak in April–July and August–November, respectively (Chen and Taylor 2002) and is separated by the Mid-Summer Drought (MSD), the magnitude of which decreases along a gradient from Central America in the west through the Greater Antilles (Cuba, Jamaica, Hispaniola and Puerto Rico) to the islands of the Lesser Antilles in the East (Figure 3; Magaña et al. 1999; Curtis and Gamble 2008; Small et al. 2007; Gamble et al. 2008; Angeles et al. 2010).

During the hurricane season (June–November), precipitation is also associated with pulses of African Easterly Waves, which transport moist and unstable air masses from the African Tropics across the region and are instrumental in the genesis of many tropical cyclones (Landsea 1993). During the winter dry season, lower SSTs and the southward migration of the ITCZ enable regional-scale subsiding air masses associated with the NAH to dominate, in turn suppressing rainfall. Any rainfall that does occur during the boreal winter is mostly localized and associated with the passage of extra-tropical cold fronts (Moron et al. 2016) that influence the islands of the Greater Antilles most and, given their more distal easterly position, least for those of the Lesser Antilles.

### 2.1 Regional climate variability and the climate of Barbuda

Given the regional precipitation variability across the Caribbean (Gouirand et al. 2012; Magaña et al. 1999), Stephenson et al. (2014) subdivided the region into six distinct climatic zones based, among other parameters, on the seasonal rainfall cycle and the timing of the summer precipitation maximum (Figure 3). The island of Barbuda falls into Zone 4, which encapsulates most of the islands of the Lesser Antilles and Puerto Rico. In contrast to the islands of the Greater Antilles, the climatology of Zone 4 does not show a significant bimodal distribution of precipitation separated by the MSD. Instead, it is replaced by a single late-season maximum in October/November (Jury et al. 2007). The mean total annual precipitation for the zone is 1311mm of which 80% falls during the May–December period, which contrasts significantly with 55–64% of mean total annual rainfall for the same period within the other zones. The equivalent value for Barbuda for the period 1965-2000 is much lower than the zonal average at 882 mm (Jackson 2001) and within this 35-year period, ten individual years were designated "meteorological" droughts. Such low levels of precipitation are best explained by the island's low-lying topography and associated lack of orographic rainfall when compared with other islands of the Lesser Antilles. Furthermore, given its location to the far northeast of the region, contributions to precipitation from extratropical cold fronts are also minimal. Thus, rainfall patterns in Barbuda are more strongly influenced by thermodynamic processes associated with Atlantic summer SSTs and the passage of African Easterly Waves and tropical cyclones than elsewhere in the Caribbean, where topographic relief and the proximity to the paths of extratropical cold fronts complicate the precipitation signal.

On interannual and multidecadal timescales Barbuda's rainfall is controlled by the relative influence of El Niño Southern Oscillation (ENSO), the Atlantic Meridional Mode (AMM; Kossin and Vimont 2007), the Atlantic Multidecadal Oscillation (AMO; Klotzbach 2011; Winter et al. 2011) and the North Atlantic Oscillation (NAO; Cook and Vizy 2010; Gouirand et al. 2012; Wang et al. 2008; Wang 2007). Interannual changes in SSTs in the eastern equatorial Pacific associated with ENSO dynamics have been shown to be strongest in the NW Caribbean diminishing somewhat towards the Lesser Antilles (Jury et al. 2007). During a developing El Niño (La Niña) event (September–December), positive (negative) SST anomalies develop in the Pacific increasing (decreasing) the surface pressure gradient between the NAH and the eastern equatorial Pacific in turn strengthening (weakening) the CLLJ. Enhanced (reduced) vertical wind shear and increased (decreased) subsidence interfere with (promote) the vertical development of tropical cells subsequently reducing (increasing) precipitation and tropical cyclone activity and resulting in dry (wet) conditions across much of the Caribbean. Above normal rainfall in the Caribbean during the boreal spring following an El Niño event (April-May) is common and associated with a warming of the tropical Atlantic (Taylor et al. 2002; Taylor et al. 2011).

The Atlantic Meridional Mode (AMM) is a dynamical mode of coupled ocean and atmosphere variability in the Atlantic and similarly operates on interannual timescales (Kossin and Vimont 2007). It manifests itself as a cross equatorial gradient in SST and a shift in the ITCZ toward the warmer hemisphere. A positive (negative) AMM decreases vertical wind shear and surface pressure, in turn shifting the ITCZ northwards (southwards) and creating environmental conditions conducive (unfavorable) to rainfall and tropical cyclone activity. On multidecadal timescales the AMM is strongly correlated with, and thought to influence, the Atlantic Multidecadal Oscillation (AMO), which is an index of North Atlantic SST variability with alternating warm and cold phases over periods of 65–70 years (Schlesinger and Ramankutty 1994). It has been shown to have a widespread influence on climatic phenomena including tropical Atlantic hurricane activity (Goldenberg et al. 2001; Klotzbach 2011) and precipitation in Africa (Folland et al. 1986; Knight et al. 2006), the Caribbean (Stephenson et al. 2014) and North America (Enfield et al. 2001) and these oscillations are clearly recorded in annual resolution coral-based SST near Puerto Rico (Kilbourne et al. 2008; Saenger et al. 2009) and across the region (Hetzinger et al. 2008; Vásquez-Bedoya et al. 2012; Tierney et al. 2015).

The NAO affects Caribbean rainfall predominantly during the boreal winter through its influence on the strength and position of the NAH (Wang 2007; Cook and Vizy 2010) and in turn the CLLJ. However, given that its influence is manifested most strongly during the annual precipitation minima of the dry season (particularly so for Barbuda) it is thought to exert less control on total mean annual rainfall than ENSO and the AMM/AMO. Nevertheless, a positive NAO in the boreal winter is characterized by a stronger NAH and CLLJ that combine to cool the ocean surface and advect moisture towards the south-west into the Gulf of Mexico and Central and South America (Martin and Schumacher 2011). The combination of moisture loss and enhanced surface pressure suppresses atmospheric deep convection causing drier conditions in the circum-Caribbean region. In contrast, during a negative NAO phase, the intensities of the NAH and CLLJ diminish, promoting convective rainfall.

## 3. The Climate of the past

### 3.1 Holocene sea level rise

One of the principal factors controlling long-term climatic change on Caribbean islands is orbital forcing of global climate. During the last glacial maximum (ca. 22,000 yrs BP; unless otherwise states all dates are quoted in calendar years before present), average Caribbean temperatures were 5–8°C cooler than today and eustatic sea levels 121 ± 5m lower (Fairbanks 1989). Orbitally-forced warming during the Holocene resulted in the melting of the Laurentide and Fennoscandian ice sheets and an increase in eustatic sea levels to their present-day level around 2–3000 years BP. This resulted in significant landscape changes across the region, particularly as it relates to island biogeography and human settlement patterns (Siegel et al. 2015). Indeed, the surface geology of Barbuda is young and has remained relatively stable tectonically throughout the Pleistocene (Brasier and Donahue 1985). Consequently, the island has been shaped by eustatic sea-level changes associated with successive glacial cycles. Furthermore, the late-Holocene origin of Freshwater Pond from which a reconstruction of local changes in effective moisture was derived, is thought to be the result of rising eustatic sea level that reached its present-day maximum level ca. 2–3000 years BP (Fairbanks 1989; Burn et al. 2016). The subsequent development of a rainfall-derived freshwater lens, which rests above the underlying saltwater table would have provided a valuable new source of fresh water to settled and/or migrating communities on the island.

### 3.2 Caribbean climate variability during the Holocene

Only a few Caribbean Climate records extend back through the Holocene into the last glacial maximum. The most continuous record is that of titanium (Ti) abundance from the Ocean Drilling Program (ODP) Site 1002 sediment archive from the Cariaco Basin, Venezuela (Figure 4). Haug et al. (2001) argue that terrigenous erosion of river catchments along the north coast of Venezuela transports sedimentary titanium to the Caribbean Sea, which subsequently sinks and becomes emplaced within the sediments of the Cariaco Basin. The sediment record therefore reflects changing rainfall amounts associated with the long-term migration of the ITCZ during the late-glacial and Holocene periods (since ~22,000 yrs BP) where increased (decreased) Ti counts represent higher (lower) rainfall. The timing and sinusoidal characteristics of the Ti record (Figure 4) suggest that the orbital precession cycle, which modifies the intensity of the seasonal cycle, is responsible for these long-term changes. Given this interpretation, the late-glacial and early Holocene periods were probably characterised by a more southerly position of the ITCZ resulting in relatively dry conditions across the Caribbean. Regional aridity at this time is further supported by terrestrial paleoclimate reconstructions from Haiti (Hodell et al. 1991), Jamaica (Street-Perrott et al. 1993; Holmes et al. 1995; Holmes 1997) Cuba (Fensterer et al. 2013) and Venezuela (Curtis et al. 2001) suggesting this to be a Caribbean-wide phenomenon.

By the Mid-Holocene (~7000-3000 yrs BP) the records suggest the mean location of the ITCZ shifted to the north and wetter conditions prevailed across the region. Such conditions were likely accompanied by changes in the biogeography of the Caribbean as is well-exemplified in the lowlands of Haiti where a transition from drought-adapted sclerophyllous vegetation to mesic forest occurred (Higuera-Gundy et al. 1999). Moister conditions were probably also more conducive for human habitation and may indeed explain initial colonization of the Caribbean ~6000 yrs BP (Keegan and Hofman 2017; Rousseau et al. 2017; Newsom and Wing 2004; Wilson, 2007) and subsequent waves of migration including that of the Saladoid culture ~2500 yrs BP (Keegan et al. 2013; Keegan and Hofman 2017; Bain et al. 2018; Le Febvre 2018). Since the late Holocene (~3000 yrs BP to present), both the Venezuelan (Cariaco Basin and Lake Valencia) and Haitian archives suggest progressive drying implicating the precession-driven southward migration of the ITCZ. In contrast, terrestrial paleoclimate reconstructions from Cuba (Fensterer et al. 2012) and Jamaica (Street-Perrott et al. 1993) suggest a trend towards wetter conditions during this period. The apparent disparities between these records may be explained by a transition towards increased regional variability in effective moisture across the region during the late Holocene, a change consistent with the variability observed in the contemporary climatology of the Caribbean (see above).

It is tempting to test the hypothesis that precession-forced and consequently time-transgressive climate variability was responsible for the different waves of human migration across the Caribbean. However, while some suggest that orbitally-forced changes in precipitation in the Caribbean appear time-transgressive (e.g. Siegel et al. 2015), this contention is not yet fully supported by the available paleoclimate archives, given the significant variability in the climate signal among archives during the late Holocene and the significant uncertainties associated with hard-water errors inherent in the radiocarbon chronologies of many Caribbean terrestrial lake sediment records (Curtis et al. 2001) and recent re-examination of multiple radiocarbon dates from archaeological archives (Napolitano et al. 2019). Further, complexities in the regional climatology and strong evidence of non-stationarity of the different modes of climate variability over time (Rodbell et al. 1999; Gray et al. 2004; Metcalfe et al. 2010; Fritz et al. 2011; Burn et al. 2016), suggest that that changing rainfall patterns in the Caribbean are not simply a function of the latitudinal migration of the ITCZ.

### 3.3 Caribbean climate variability during the late-Holocene

A growing number of paleoclimate reconstructions of climatic dynamics during the last millennium now exist for the Caribbean Region. These include SST reconstructions dating back to the mid 16th Century (Kilbourne et al. 2008; Hetzinger et al. 2008; Vásquez-Bedoya et al. 2012; Tierney et al. 2015), lake sediment records of changing effective moisture (E.g. Hodell et al. 2005; Lane et al. 2011; Burn and Palmer 2014; Burn et al. 2016), high-resolution speleothem (e.g. Kennett et al. 2012; Fensterer et al. 2012) and tree-ring records (Trouet et al. 2016) and documentary archives of climate phenomena (García-Herrera et al. 2005; Chenoweth 2007; Chenoweth and Divine 2008, 2014; Berland et al. 2013; Berland and Endfield 2018). Each of these reconstructions provides a snap shot of climate variability at a specific location at different temporal resolutions. Here, we focus on climate reconstructions relevant to specific archaeological periods both at the regional and local scales.

#### 3.3.1 Climate variability during the Colonial Period

The Colonial Period in the Caribbean occurred at a time where average temperatures in the circum-North Atlantic region dropped significantly during the period known as the Little Ice Age (LIA). Paleoclimate and historical records reveal significant reductions in North Atlantic atmospheric temperatures (Mann et al. 2009; Jones et al. 2009), SSTs (Keigwin 1996; Marchitto and DeMenocal 2003) as well as increases in Arctic sea-ice extent (Broecker 2000; Vare et al. 2009) and alpine glacial advances (Holzhauser et al. 2005). These climatic changes are thought to be attributed to reduced radiative forcing caused by a combination of lower solar activity resulting from four grand solar minima (Wolf, Spörer, Maunder and Dalton) and increased volcanic activity (Wanner et al. 2008; Jones et al. 2009; Mann et al. 2009; Bindoff et al. 2013).

The paleoclimate evidence from across the Caribbean confirming the footprint of the LIA is reasonably abundant (Haug et al. 2001; Hodell et al. 2005; Lane et al. 2011; Burn and Palmer 2014). Most records suggest the LIA manifested itself as a cooler and drier period punctuated by region-wide drought events, which would have resulted in depleted water resources and acted as a stressor to established cultures across the region. Individual paleoceanographic reconstructions suggest that Caribbean SSTs may have decreased by ca. 2–3°C during the LIA (Winter et al. 2000; Watanabe et al. 2001; Nyberg et al. 2002; Haase-

Schramm 2003; Black et al. 2007; Saenger et al. 2009), which would have suppressed rainfall by inhibiting both the northward extension of the ITCZ and atmospheric convection.  However, a more statistically robust composite record of coral-based SST reconstructions for the tropical Atlantic and Caribbean suggests the regional drop in mean sea-surface temperatures decreased by just 0.6°C during the LIA (Tierney et al. 2015). Nevertheless, the impact of the latter estimate would have similarly reduced the amount of available thermal energy, in turn lowered evaporation rates and resulted in significant reductions in precipitation. There would also have been a significant reduction in rainfall associated with supressed tropical cyclone activity, the genesis of which requires sea-surface temperatures in excess of 26°C (Gray 1968).

A suite of terrestrial paleoclimatic archives supports the coral-based paleoceanographic reconstructions that indicate lower SSTs resulted in drier conditions during the LIA (Haug et al., 2001; Hodell et al., 2005; Metcalfe et al., 2010; Lane et al., 2011; Fensterer et al., 2012). The titanium record from the Cariaco Basin (Haug et al., 2001) and oxygen isotope measurements from a lake sediment record in Aguada X'caamal (Hodell et al., 2005) on the Yucatan Peninsula in Mexico, suggest dry periods punctuated the circum-Caribbean region between 1450 and 1800 CE. Further support for a coherent regional drought response to low natural radiative forcing during the LIA may be garnered from a 1500-year reconstruction of glacial advance from a proglacial lake sediment record recovered from Lago Mucubaji in the Venezuelan Andes (Polissar et al. 2006). The magnetic susceptibility record from this site differentiates between sedimentation of clastic minerogenic material and authigenic sediment production. Higher levels of clastic sedimentation during the Wolf, Spörer, Maunder and Dalton grand solar minima are interpreted as periods of glacial advance. Ice accumulation occurred because of increased orographic rainfall associated with a stronger CLLJ, which enhanced the flux of advected moisture to the Venezuelan Andes. Together these sites support inferences drawn from other paleoclimatic archives within the circum-Caribbean region (Hodell et al., 2005; Metcalfe et al., 2010; Lane et al., 2011) that suggest a strong influence of natural radiative forcing on regional drought patterns over the last millennium.

In contrast, recent paleoclimate reconstructions from Belize (Kennett et al. 2012), Cuba (Fensterer et al., 2013), Jamaica and Barbuda (Burn and Palmer, 2014; Burn et al., 2016) suggest that long-term changes in effective precipitation during the LIA were much more variable, temporally and spatially, in turn indicating that the coupled ocean-atmosphere climate modes ENSO and AMO may override, or are at least superimposed upon, the influence of natural radiative forcing. Kennett et al. (2012) present results from a high-resolution speleothem record from Belize and argue that precipitation variability was driven by a combination of the long-term migration of the ITCZ and ENSO dynamics with drier (wetter) periods associated with El Niño-like (La Niña-like) conditions. They draw on contemporary climatology to argue that during an El Niño event, during which positive SST anomalies dominate the tropical Pacific, a decrease in surface pressure associated with the Pacific ITCZ increases the North Atlantic-equatorial Pacific pressure gradient, in turn resulting in a stronger CLLJ, enhanced wind shear and drier conditions across the Caribbean. Moreover, Fensterer et al. (2012) present a high-resolution oxygen isotope record from a speleothem in western Cuba and demonstrate a strong correlation between local precipitation and multidecadal variability of Atlantic SSTs during the last 1300 years. The authors show that there is no clear drying response in Cuba to either the grand solar minima or volcanic activity and that their record is most likely explained by long-term changes in the AMO.

In Barbuda, the lake sediment record from Freshwater Pond exhibits a more complex response to climate forcing during the LIA. Burn et al. (2016) present a ~400-year reconstruction of effective precipitation for Barbuda since the mid-16th century based on biostratigraphic and stable oxygen isotope analyses of fossil ostracods and gastropods recovered from lake sediment cores (Figure 5). Episodic fluctuations in shell accumulation in the sediment record represent changes in the balance between precipitation and evaporation during the LIA and Industrial (1850 CE–present) periods. To examine the influence of these modes of climate variability on the long-term effective rainfall in Barbuda, Burn et al. (2016) compared the abundance of the freshwater gastropod *Pyrgophorus parvulus* and an oxygen isotope record from ostracod calcite from Freshwater Pond with high-resolution tree-ring based reconstructions of the AMO (Gray et al. 2004) and ENSO (Li et al. 2013). The strong correspondence between the abundance of *P. parvulus* and the AMO reconstruction between about 1550 and 1850 CE suggests that extended episodes of aridity were best explained by suppressed SSTs in the tropical Atlantic. Similarly, periods of increased effective moisture were mostly associated with warmer Atlantic SSTs. The covariance between these two proxy records suggests that during the LIA, SST variability in the Atlantic had a greater influence on rainfall patterns in Barbuda than natural radiative forcing for which no evidence was found. Given Barbuda's proximity to the center of AMO activity in the Tropical Atlantic, the close correspondence between Atlantic SST and rainfall patterns seems intuitive.

Further comparison of the Freshwater Pond sequence with the ENSO reconstruction of Li et al. (2013; Figure 5) suggests that ENSO has also had a strong influence on rainfall patterns in Barbuda during the LIA, particularly since 1700 CE. Episodes of stronger El Niño-like activity occurred during the periods 1720–1775, 1820–1850 and 1975–2010 CE and were associated with drier conditions as represented by the low abundance of *P. parvulus* and more positive $\delta^{18}$O values. In contrast, inferred wetter periods between 1775 and 1800 CE and during the late 19th century correspond with La Niña-like conditions in the tropical Pacific. Given that contemporary rainfall patterns in the region are strongly controlled by the interplay between ENSO and the AMO, the changing rainfall patterns represented in the Barbuda record also appear to reflect the relative influences of these regional-scale climatic phenomena.

### 3.3.2 Documentary Sources from Antigua

Documentary sources of climate variability in the Caribbean include missionary, plantation and governmental papers, and provide climate information at high temporal resolutions that are poorly resolved in most natural environmental archives. Comparison between documental and natural lake sediment archives is difficult give the chronological precision of the former and the decadal-centennial-scale uncertainties inherent in most radiocarbon-based chronologies of the latter. Berland et al. (2013) present the first archival investigation of precipitation variability between 1770 and 1890 CE from the island of Antigua, located less than 100 km to the south of Barbuda. They identified significant dry phases in the years 1775–80, 1788–91, 1820–22, 1834–37, 1844–45, 1859–60, 1862–64, 1870–74 and 1881–82 CE, while wet episodes were 1771–74, 1833–34, 1837–38, 1841–44, 1845–46 and 1878–81 CE. Despite the difficulties comparing archival records of different temporal resolutions, there are some significant similarities between these results and the sediment-based reconstruction from Freshwater Pond in Barbuda that fall within the error margins of the radiocarbon chronology of Burn et al. (2016; Figure 5). Berland et al. (2013) reported the most severe drought of the study period in Antigua to have occurred during the late 1770s CE, an episode characterized by severe precipitation deficiency and multi-year harvest failures. Such drought conditions are consistent, within the margins of error of the radiocarbon chronology, with an extended episode of dry conditions in Barbuda between ~1720–1780 CE (Unit FP3) characterized by the low abundance of the freshwater gastropod *P. Parvulus*, more positive $\delta^{18}$O excursions of ostracod calcite and persistent El Niño-like conditions in the equatorial Pacific (Burn et al. 2016). In contrast, Berland et al. (2013) report a sustained increase in rainfall from the early 1870s to the mid 1880s CE, which is consistent not only with local meteorological records but also with the rapid transition from a period of extreme aridity recorded at Freshwater Pond at ~1865 CE, similarly characterized by a low abundance of gastropods and positive $\delta^{18}$O values, to wetter conditions in the 1880s. Such comparisons lend credibility to both reconstructions. Moreover, the sediment-based reconstruction of effective moisture provides the longer-term paleohydrological context within which the more detailed documentary reconstruction may be understood, whereas the documentary source provides specific detail that is often-times poorly-resolved in the sediment record.

## 4 Future Climate Projections

Projected climate change in the 21st Century is of significant importance for the SIDS of the Caribbean, which are extremely vulnerable to multiple climate stressors including Sea-level Rise (SLR), the passage of tropical cyclones, increasing air and SSTs, and extended episodes of drought (Nurse et al. 2014). Here, we review the global climate projections from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) and discuss how these projected climatic changes are manifested at the regional (Caribbean-wide) and local (Antigua and Barbuda) scales.

### 4.1 Global climate projections

The AR5 of the IPCC identifies four Representative Concentration Pathways (RCPs) for different projections of future greenhouse gas (GHG) concentrations. RCP 2.6 assumes that global annual GHG concentrations peak between 2010–2020 CE at 3 $Wm^{-2}$, declining substantially thereafter; those in RCP 4.5 peak and stabilize at 4.5 $Wm^{-2}$ around 2040 CE; in RCP 6.0, GHGs peak and stabilize around 2080 CE; and lastly, in RCP 8.5, concentrations reach 8.5 $Wm^{-2}$ by 2100 CE and continue to rise thereafter (Cubasch et al. 2013). In general, RCP 4.5 is used by most climate practitioners and represents an intermediate total radiative forcing pathway coupled with a positive global GHG forcing of 4.5 $Wm^{-2}$ by 2100. It is a mitigation-based, and arguably more realistic, pathway that assumes positive human intervention, such as global uptake of renewable energy sources to avoid a runaway warming climate, of which the latter is represented by the fossil-fuel intensive RCP 8.5 scenario with a positive GHG forcing of 8.5 $Wm^{-2}$ by 2100 (Taylor et al. 2018).

In terms of temperature, the average mean global temperature is projected to exceed 1.5°C for all RCP scenarios relative to 1850–1900 CE, 2°C for RCP 6.0 and RCP 8.5, and more likely than not 2°C for RCP 2.6. As a result, global sea levels have been rising at a rate of 3.2 mm per year since 1993 (NOAA, 2018), although there are local and regional differences due to the consequences of the vertical land movement and the eustatic sea level due to thermal expansion and melting land glaciers. Global mean sea level will continue to rise in the 21st century at a faster rate. The amount of rise varies from 0.26–0.55 m for RCP 2.6 to 0.45–0.82 m for RCP 8.5, and between 0.4–0.7 m for the RCP 4.5 scenario (Christensen et al. 2013).

### 4.2 Future climate projections for the Caribbean

Taylor et al. (2018) present projections of temperature and precipitation for the Caribbean region based on three global warming scenarios: projections for a world whose pre-industrial mean temperature (1861–1900) has been exceeded by global mean annual air temperature anomalies of 1.5°C, 2°C and 2.5°C (designated $\Delta T_g 1.5$, $\Delta T_g 2$, $\Delta T_g 2.5$; Taylor et al., 2018). They simulate near-surface temperature and precipitation values using 10 General Circulation Models (GCMs) from the Coupled Model Intercomparison Project phase 5 (CMIP5) for RCP 4.5. Each of the 10 selected GCMs was able to capture the characteristic bi-modal rainfall pattern of the Caribbean (Figure 3) and is considered to be a good representation of the regional climatology. Here, we summarise the future temperature and precipitation states for the Caribbean using RCP 4.5 and for the global warming scenarios $\Delta T_g 1.5$, $\Delta T_g 2.0$, and $\Delta T_g 2.5$.

When compared with the pre-industrial baseline, temperature projections for the Caribbean show a significant increase in mean annual temperature anomalies of 1.2 ± 0.2°C ($\Delta T_g 1.5$) by 2028, 1.6 ± 0.3°C ($\Delta T_g 2.0$) by 2046, and 2.0 ± 0.3°C ($\Delta T_g 2.5$) by 2070 (Taylor et al. 2018). These estimates are consistent with previous regional model projections, which show temperature increases spanning 1.0–3.5°C by the end of the 21st century (Campbell et al. 2011; McSweeney et al. 2012; Karmalkar et al. 2013). Regional variability is expressed by enhanced (reduced) warming on larger (smaller) land masses such as the Greater (Lesser) Antilles. The associated sea level rise in the Caribbean region is estimated to be close to the global mean at 0.5 to 0.6 m by 2100 for RCP 4.5 (Nurse et al. 2014).

The projected precipitation regime for the region is characterised by significant spatial and temporal variability, which resembles the complexity of past and present climate systems of the Caribbean described above. Under the $\Delta T_g 1.5$ scenario, much of the region is expected to show an increase in precipitation with a maximum increase in the southwestern Caribbean associated with enhanced moisture transport within the CLLJ (Taylor et al., 2018). In contrast, the north- and southeast Caribbean islands including the islands ranging from Puerto Rico to Antigua and Barbuda as well as the Netherlands Antilles, are expected to experience a slightly drier climate. Under the $\Delta T_g 2.0$ and $\Delta T_g 2.5$ scenarios, the entire region, with the exception of the Bahamas, exhibits a drying trend of between 5–20% with spatial variability still being significant. Projected changes in rainfall intensity correspond to those of precipitation anomalies where the number of days of the year when precipitation exceeds 10 mm increase for $\Delta T_g 1.5$ and then decrease progressively for $\Delta T_g 2.0$ and $\Delta T_g 2.5$ (Taylor et al., 2018). Given the lack of a concerted effort towards a low-carbon global economy, a pragmatic approach would adopt the $\Delta T_g 2.0$ and $\Delta T_g 2.5$ scenarios as the most realistic global warming targets. Consequently, under the current GHG trajectory, it is likely that the Caribbean will experience a progressive drying trend by 2100 that is characterised by a more intense CLLJ and fewer intense rainfall days.

The impact of 21st Century climate change on Atlantic tropical cyclones is poorly understood. The IPCC AR5 (2013) report, informed by the work of Knutson et al. (2010), concluded that there is low confidence in region-specific projections of tropical cyclone activity and that it remains uncertain whether recent changes in Atlantic tropical cyclone activity lie outside the range of natural variability (Christensen et al., 2013). Such uncertainty makes it difficult for SIDS to plan for the significant socio-economic and cultural consequences of 21st Century global warming. Nevertheless, there is a broad scientific consensus that there will be a substantial decrease (ca. 25%) in the frequency of tropical cyclones, which is consistent with 21st Century projections of reduced precipitation, a stronger CLLJ and enhanced vertical wind shear in the tropical Atlantic. Given anthropogenic warming of Atlantic SSTs, however, it is considered likely that storms will become more intense and exhibit higher rainfall rates than contemporary tropical cyclones (Bender et al., 2010). Thus, the likely response of Atlantic tropical cyclones to anthropogenic climate change is a transition to fewer than average tropical cyclones with greater intensity. Arguably, SIDS of the Caribbean should therefore assign greater importance to the expected increased vulnerability of their coastlines to greater storm-surge flooding associated with future sea level rise and coastal development.

### 4.3 Impact of projected 21st Century climate change on ENSO and the AMO

Given the strong influence of ENSO and the AMO on climate phenomena in the Caribbean, the future dynamics of coupled ocean-atmosphere variability in the Pacific and Atlantic Oceans needs to be considered when projecting 21st century climate. However, the extent to which these modes of climate variability respond to anthropogenic climate change is poorly understood. Contemporary SST anomalies in the tropical Atlantic have shown a consistent negative trend since 2013 prompting Klotzbach et al. (2015) to suggest a transition may be underway from the positive AMO phase of enhanced rainfall and tropical cyclone activity that characterised the period 1995–2012, to a negative phase that would portend less rainfall and tropical cyclone activity for at least half an AMO cycle (Goldenberg et al., 2001). Such conditions superimposed on the projected progressive drying trend linked to 21st century anthropogenic warming, would act to further suppress rainfall and tropical cyclone activity.

The response of ENSO to 21st Century climate change is equally poorly understood; however, recent studies have provided further insights into the link between the changing mean state of the eastern equatorial Pacific and ENSO dynamics. In a comprehensive review of empirical and climate model data, Cai et al. (2015) show that the accelerated warming of eastern equatorial Pacific SSTs associated with a reduced Walker circulation, is expected to increase extreme rainfall and the equatorward migration of the Pacific ITCZ, both of which are features of an extreme El Niño event. The authors argue further that the frequency of extreme La Niña events is also expected to increase and that ENSO-related extreme weather events are likely to occur more frequently under 21st century global warming. In the Caribbean, this would manifest itself as a greater magnitude of interannual variability between episodes of extreme rainfall and tropical cyclone activity, and those of drought. Arguably, the transition from the extreme Caribbean-wide droughts of the 2015–2016 El Niño to the very active and record-breaking Atlantic hurricane seasons of 2017 and 2020 (both La Niña years) are consistent with this hypothesised pattern of extreme ENSO-related climate phenomena.

### 4.4 Future climate change in Barbuda

The impact of SLR is likely not only to exacerbate coastal flooding and the concomitant erosion of mangrove and coral reef ecosystems, but also enhance the devastation from storm surges associated with the passage of tropical cyclones and tsunamis, as well as promote saline intrusion and the associated degradation of potable groundwater resources, a particular problem for islands composed of a porous limestone geology. The impact of rising sea-levels on Barbuda is already unmistakable, characterised by enhanced levels of saline intrusion (Boger et al. 2014), greater susceptibility to hurricane-induced marine washover events, the consequent harmful effects of elevated soil salinity (Boger et al. 2016), and the increasingly rapid erosion of terrestrial and marine ecosystems as well as archaeological sites located along the island's coastlines (Perdikaris et al. 2018). A recent report from the Permanent Service for Mean Sea Level (PSMSL) estimated a negative vertical land movement of -0.070 mm per year for Barbuda, which approximates to ~0.5 m of SLR by the year 2100, a more conservative estimate of the extent of the impact from SLR compared with the 0.7 m SLR calculated by the IPCC AR5 report (Christensen 2013). Under a 0.5 m SLR scenario, Barbuda would lose ~30% of its total land area as shown by a recent Digital Elevation Model (DEM) of SLR (Figure 6). In particular, the eastern and northern coastal low-lying areas are particularly susceptible to the impacts of SLR including areas in close proximity to Codrington, the island's only village.

Available freshwater has always been a significant challenge in Barbuda due to its low topography, limited rainfall, porous limestone geology and limited capacity to store water. Given the projections of regional drying during the 21st Century, Barbuda is also likely to experience drier conditions in the immediate future under $\Delta T_g 1.5$, $\Delta T_g 2.0$ and $\Delta T_g 2.5$ global warming scenarios. Superimposed on this trend, the island may experience extended periods of drought associated with the negative phases of the AMO and pronounced periods of extreme rainfall and drought associated with the increased amplitude of variability of the ENSO cycle (Cai et al. 2015; Klotzbach 2011). In 2018, Barbuda experienced extreme drought leading the Caribbean Climate Outlook Forum (CariCOF) to put a drought watch in place for Antigua and Barbuda for long-term drought conditions through the winter of 2018/19. Subsequent El Niño conditions extended from September 2018 through May 2019 causing widespread drought. Given that Elder et al. (2014) found a positive correlation between drought conditions between the AMO and the Standardized Precipitation Evapotranspiration Index (SPEI; negative values of SPEI indicate drought). it appears that combined AMO and El Niño-like conditions contributed to the severe drought that Barbuda faced in 2018/2019. Taken together, the devastating impacts of Hurricane Irma in 2017 (discussed below) combined with an extended drought in 2018/19, had a significant impact on both terrestrial and marine ecosystems of Barbuda as well as its intangible and tangible heritage (Boger et al. 2019), which could mark a profound change in social, cultural and ecological dynamics.

In addition to the direct loss of land due to SLR, large areas of Barbuda are also affected by the storm surges associated with the passage of tropical cyclones. While the frequency and intensity of future storms are poorly-resolved in global and regional climate models, it is generally thought that the number of intense hurricanes (category 3 and above) will likely increase (Knutson et al. 2010). In September 2017, Hurricane Irma hit Barbuda directly as a category 5 hurricane and caused massive destruction to both its natural and built environments. Figure 7 shows a DEM of those areas inundated by Hurricane Irma's 2.43 m storm surge (Cangialosi et al. 2018) as well as those identified by visual assessments of storm debris and by consultation with inhabitants who experienced the hurricane (Boger; unpublished data). The figure shows that a large proportion of the total population of Barbuda who live in the village of Codrington were affected by the surge. Indeed, the combined damage of storm surge, rain and wind, resulted in 90–95% or more of the built environment being severely impacted by the hurricane (Cangialosi et al. 2018). Considering the projected 21st Century SLR for Barbuda, similar magnitude storm surges in the future will likely be more devastating as they penetrate further inland. Furthermore, recent research by Rivera-Collazo (2019) highlights the disparity between predictive modelling of climatic impacts in contrast with the actual damage to local cultural and heritage resources. These are important considerations as Barbuda recovers from Hurricane Irma and explores ways to increase resiliency to projected 21st Century hurricane activity.

The increased salinization of surface-fed groundwaters and soils owing to the washover of sea water during a hurricane is a further challenge to future agriculture in Barbuda and is the subject of ongoing scientific research on the island (Boger et al. 2016). Indeed, initial soil salinity measurements taken in January 2018 show high salinity values >3 mS/cm (R. Boger; unpublished data) in the surge area. When combined with the likely drop in effective precipitation associated with projected 21st Century drying, the increased salinity of soil and groundwater will likely result in lower levels of potable fresh water in the coming decades than was previously estimated. Large stretches of agricultural land were affected by the salinization associated with the storm surge from Hurricane Irma. As a result, inhabitants may increasingly need to grow crops that are better adapted to saline soils as well as adopt new agricultural techniques designed for growing in saline soil and brackish groundwater (Boger et al. 2016).

## 5 Conclusions

The aim of this chapter was to examine the nature of Barbuda's climate within the broader context of the climate dynamics of the Caribbean region and beyond. Guided by the principles of uniformitarianism, we emphasise that a comprehensive understanding of contemporary climate dynamics of the Caribbean is essential to inform us not only about the history of climate of the region, but also about the possible trajectories of future climate scenarios. From an archaeologist's perspective, such knowledge facilitates direct comparisons between the histories of human settlement and climate and helps us decipher the extent to which human activities and migration were determined climatically. However, the evidence that underpins our knowledge of contemporary and past climate variability within the region is sporadic and further collection and analyses of climate and paleoclimate data is required before we can truly understand the spatial and temporal complexity of Caribbean climate dynamics and its potential relationship with human activity in the past, present and future.

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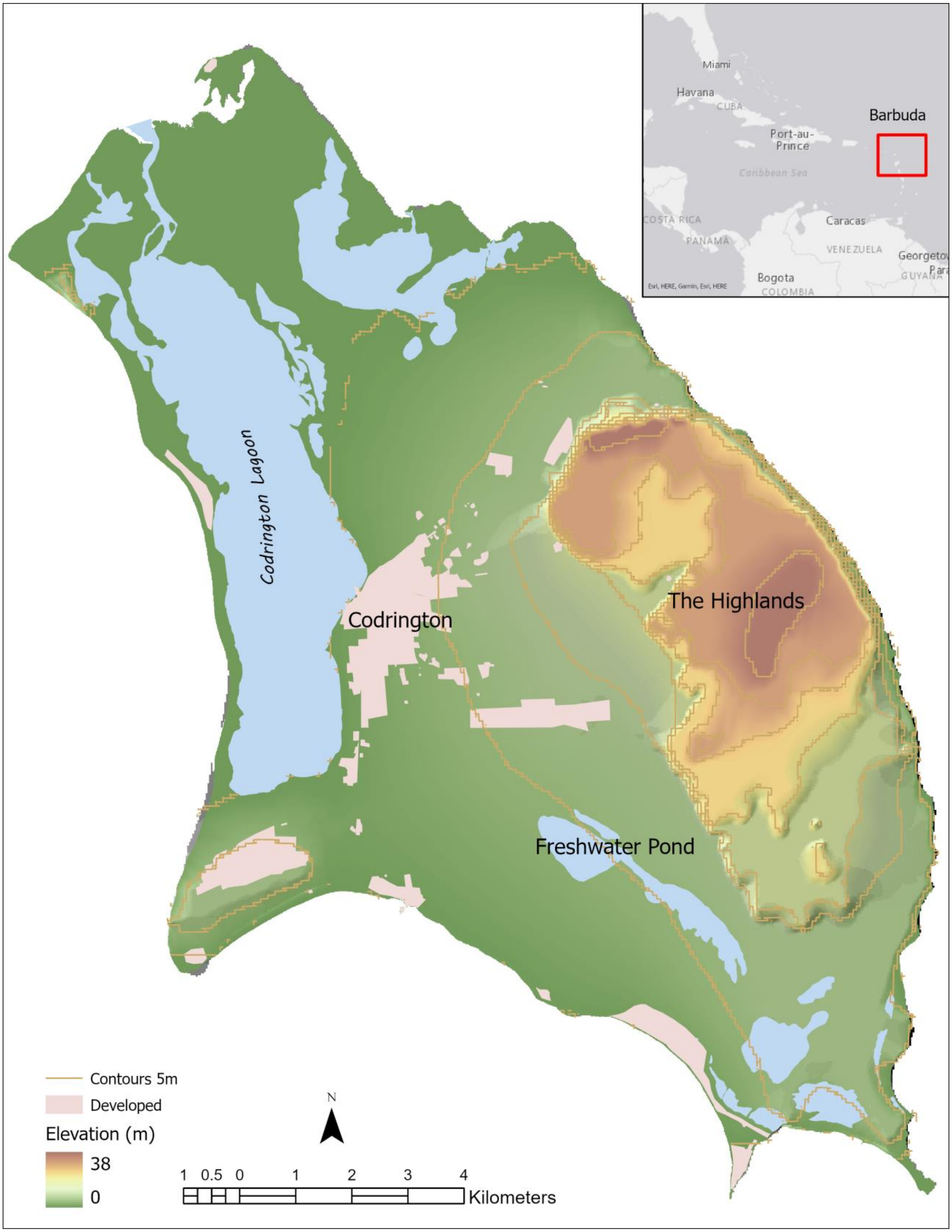
Miami
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COSTA RICA
PANAMA
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VENEZUELA
Georgetow
GUYANA
Para
Bogota
COLOMBIA
Esri, HERE, Garmin, Esri, HERE
Codrington Lagoon
Codrington
The Highlands
Freshwater Pond
Contours 5m
Developed
Elevation (m)
38
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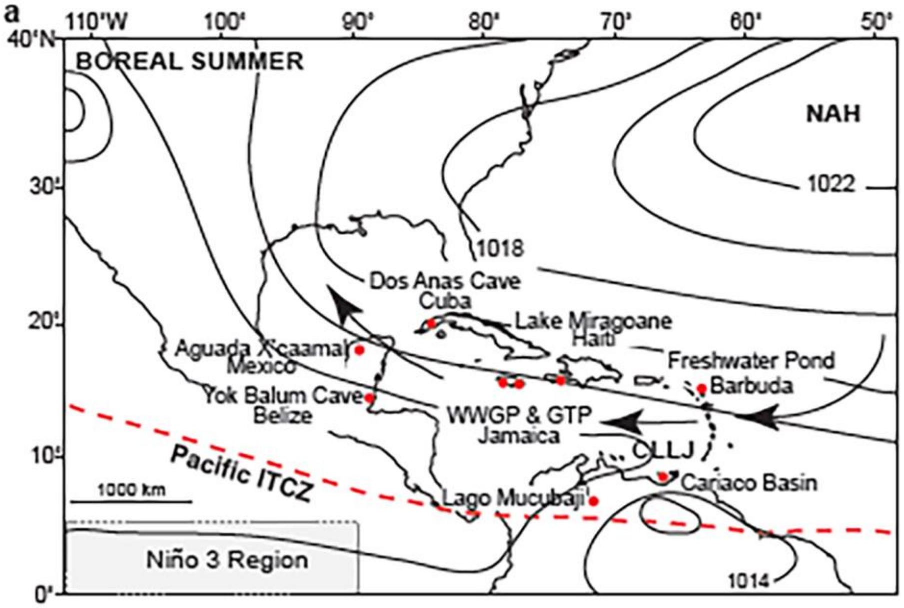
Kilometers


a
110°W
100°
90°
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30°
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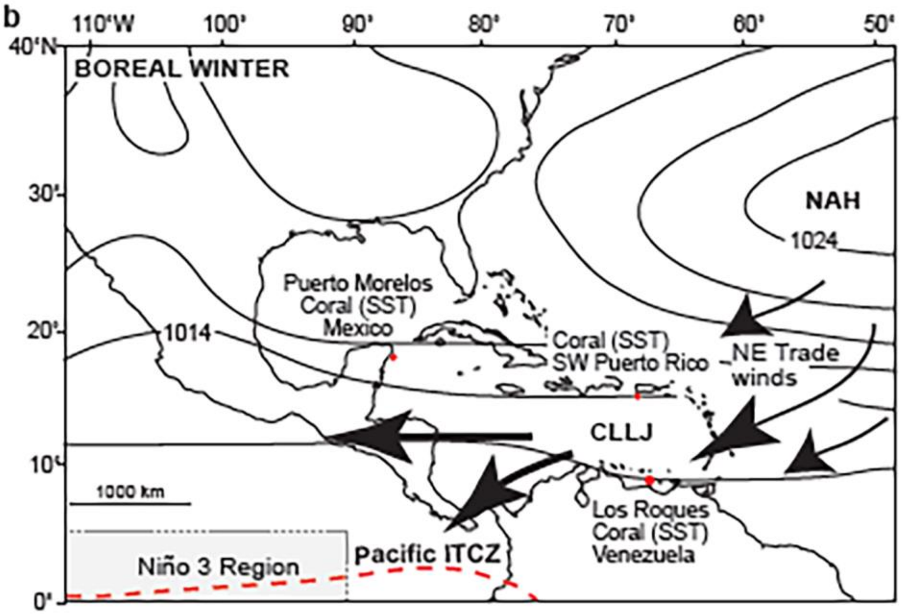
0°
BOREAL SUMMER
NAH
1022
1018
1014
Dos Anas Cave
Cuba
Lake Miragoane
Haiti
Freshwater Pond
Barbuda
Aguada X'caamal
Mexico
Yok Balum Cave
Belize
WWGP & GTP
Jamaica
CLLJ
Cariaco Basin
Pacific ITCZ
Lago Mucubaji'
1000 km
Niño 3 Region


b
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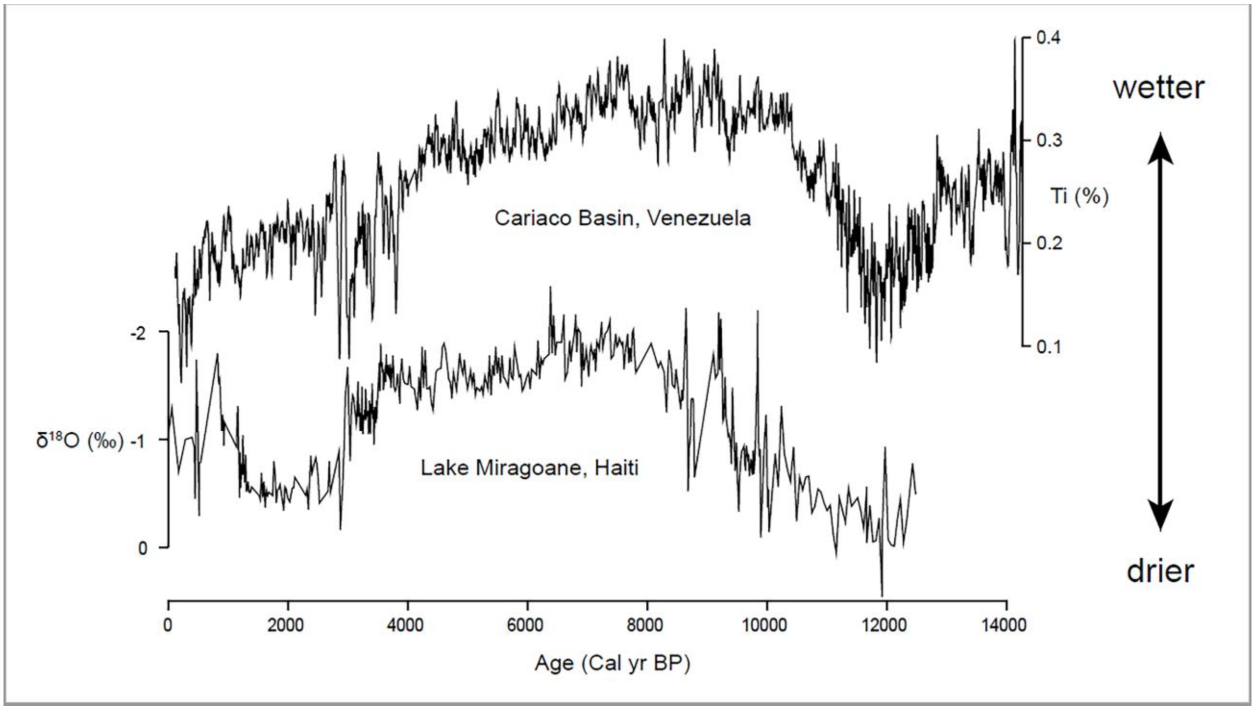
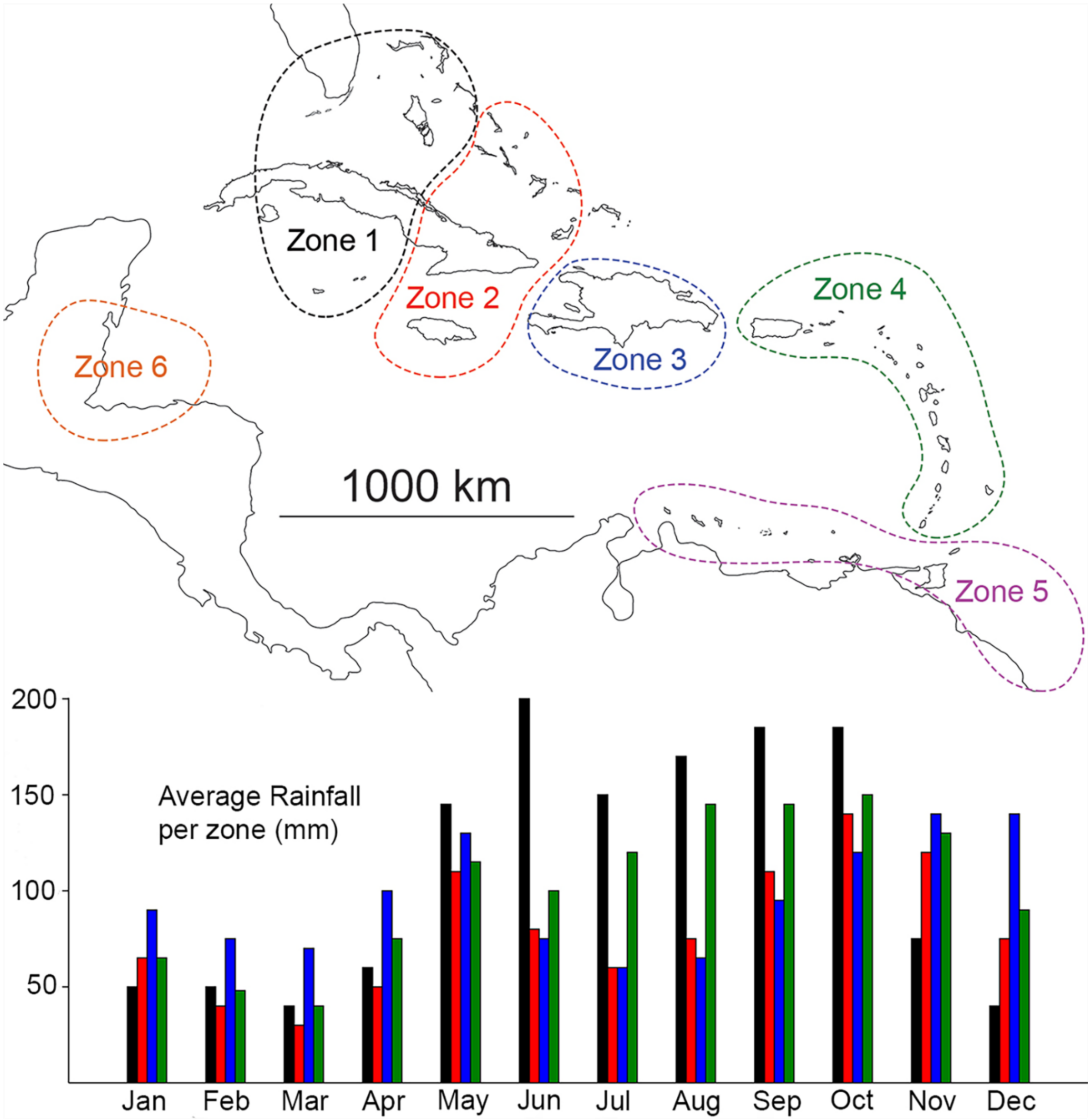
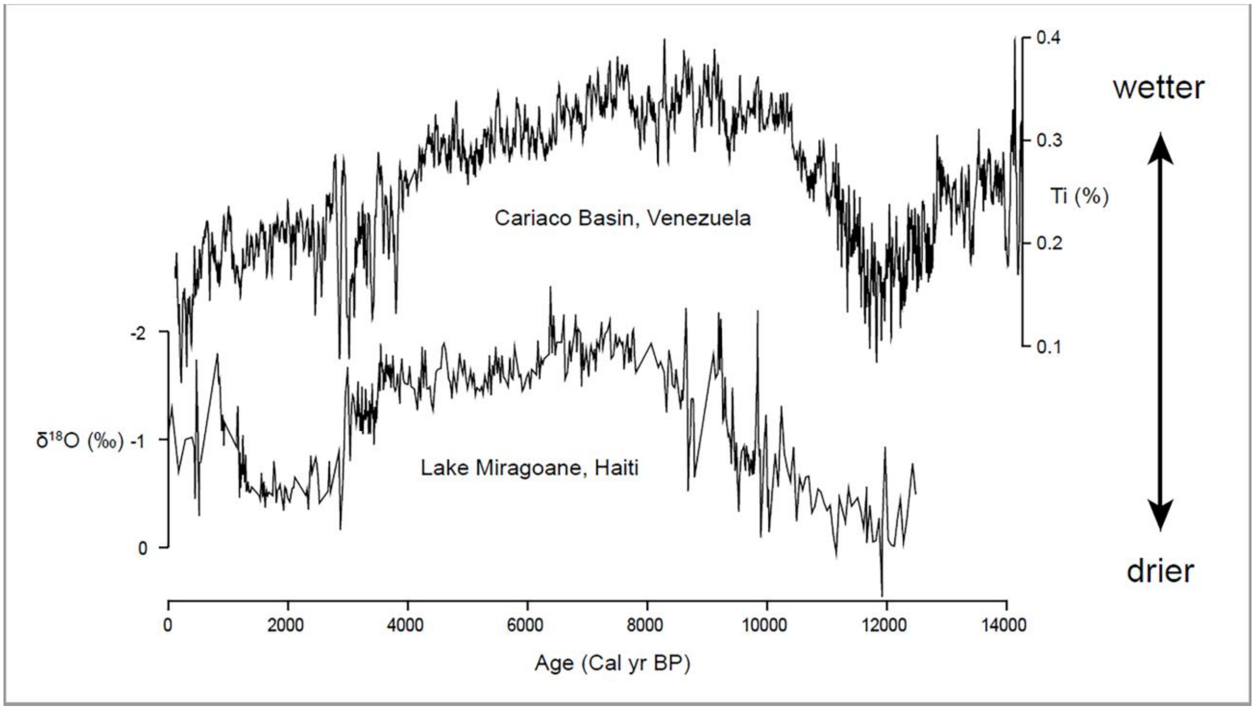
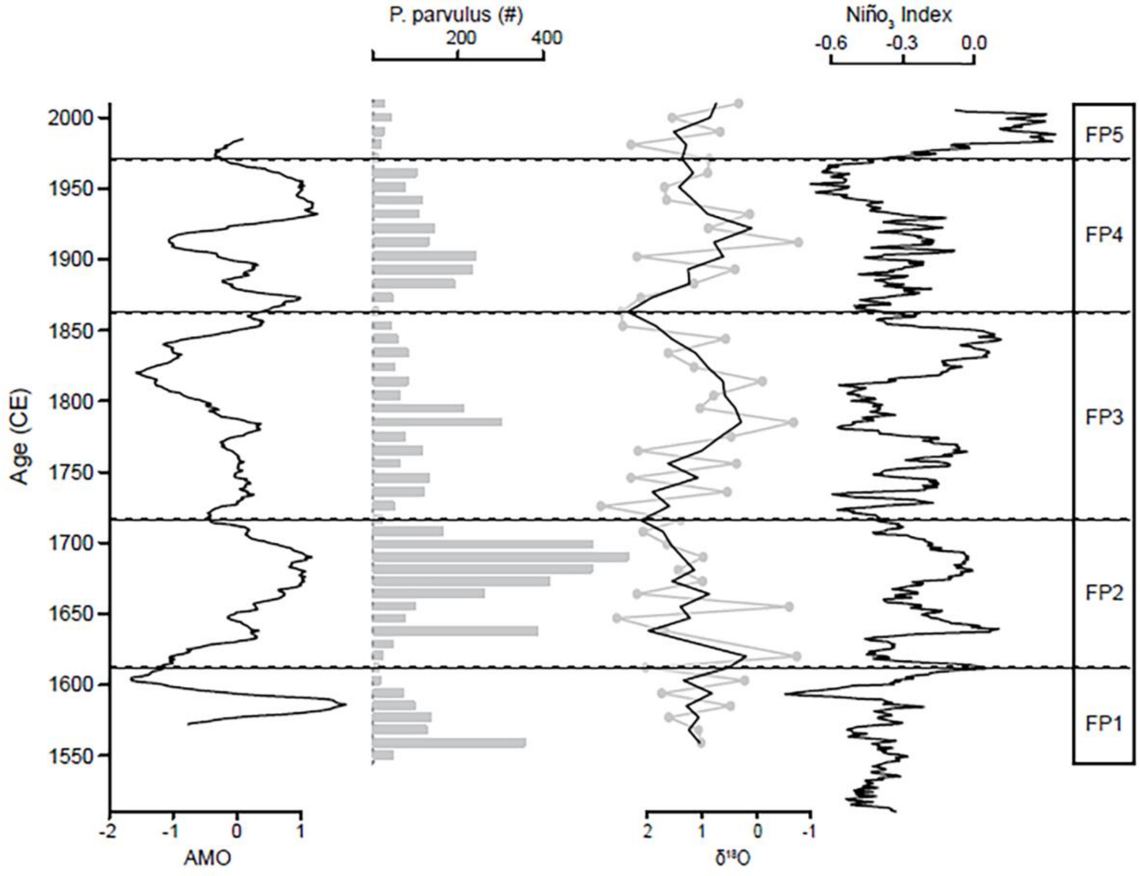
BOREAL WINTER
NAH
1024
1014
Puerto Morelos
Coral (SST)
Mexico
Coral (SST)
SW Puerto Rico
NE Trade
winds
CLLJ
Los Roques
Coral (SST)
Venezuela
1000 km
Niño 3 Region
Pacific ITCZ



0.4
0.3
0.2
0.1
Ti (%)
wetter
drier
Cariaco Basin, Venezuela
-2
δ18O (‰) -1
0
Lake Miragoane, Haiti
0
2000
4000
6000
8000
10000
12000
14000
Age (Cal yr BP)


Zone 1
Zone 2
Zone 3
Zone 4
Zone 5
Zone 6
1000 km
Average Rainfall
per zone (mm)
200
150
100
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


wetter
drier
Cariaco Basin, Venezuela
Lake Miragoane, Haiti
Ti (%)
0.4
0.3
0.2
0.1
δ¹⁸O (‰)
-2
-1
0
0
2000
4000
6000
8000
10000
12000
14000
Age (Cal yr BP)


P. parvulus (#)
200
400
Niño3 Index
-0.6
-0.3
0.0
Age (CE)
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
FP5
FP4
FP3
FP2
FP1
-2
-1
0
1
AMO
2
1
0
-1
δ¹⁸O

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Sea level rise of 0.5 meters by 2100. Inundated areas are shown in red.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

A value of 2.63 meters was used as the height of the storm surge for Hurricane Irma. This was applied to the Digital Elevation Model (DEM) and modified by field observations. Areas in orange are within the storm surge. The Palmetto area shown in yellow was likely flooded although the DEM does not indicate this. Additional field work and DEM refinement will improve these estimates.

DEM source: USAID/OAS, http://www.oas.org/pgdm/data/gis_data.htm

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