

Research papers

Tracking changing water budgets across the Bahamian archipelago

P. Spellman^{*}, A.B.C. Pritt, N. Salazar

School of Geosciences, University of South Florida, United States



ARTICLE INFO

This manuscript was handled by Emmanouil Anagnostou, Editor-in-Chief, with the assistance of Xinyi Shen, Associate Editor

Keywords:

Carbonate Island Hydrology
Freshwater lens
Remote sensing
Water budgets
Reanalysis data

ABSTRACT

Freshwater resources on small island nations are already at risk from sea level rise and groundwater pumping however, increasing aridity due to climate change further stresses water availability. The amount of freshwater availability on small island nations is delicately balanced by incoming precipitation (P) and outgoing evapotranspiration (ET). As climate changes, some island nations may see increasing aridity ($ET > P$) which can have implications for long term freshwater sustainability. Understanding how P and ET are changing allows small island nations to make more informed planning decisions regarding sustainable management and to adapt contemporary strategies to accommodate future change. The Bahamas is one such nation made up of over 700 small islands, many of which rely on freshwater lenses for potable water and irrigation. We use precipitation obtained from the TerraClimate reanalysis dataset and satellite derived actual evapotranspiration (ET_a) to analyze how seasonal and yearly water budgets have changed over the last 16 years. We show that ET_a is increasing across the Bahamas at a higher rate than global averages. The cause of ET_a increases is driven by both increases in temperature and water availability from shifting precipitation patterns, ultimately driving decreases in the amount of available water to recharge the freshwater lens.

1. Introduction

The availability of freshwater resources on many small islands ($<2000 \text{ km}^2$) is an increasing concern as climate changes and sea levels rise (Falkland and Custodio, 1991; IPCC, 2014). Climate fluctuations such as shifting precipitation patterns and magnitudes, coupled with increasing temperature and subsequent changes in evapotranspiration (ET) will impact the overall available water that can recharge freshwater lenses - a common source of potable water and irrigation for many islands. Small islands, particularly low-lying ones, are some of the most sensitive due to size and aquifer permeability. Thus, accurate water budgets are necessary to inform water management planning strategies now and in the future.

The amount of recharge to a small island freshwater lens is primarily controlled by precipitation and ET while geology and geometry are secondary controls on overall available storage volumes (Budd and Vacher, 1991; Vacher and Wallis, 1992; Schneider and Kruse, 2003; van der Velde et al., 2006; Bailey et al., 2010; Holding and Allen, 2014). Freshwater for many small islands exists as a lens that sits atop and interacts with the underlying seawater (Budd and Vacher, 1991). The volume of freshwater availability is dependent upon the available aquifer storage which exponentially decreases with island size and elevation

above sea level (Vacher, 1988; White and Falkland, 2009). Recharge to the freshwater lens is primarily governed by the balance between precipitation and ET as carbonate landscapes (e.g. islands) with little relief and porous substrate do not typically support surface drainage (Ford and Williams, 2013; Worthington, 2001; Whitaker and Smart, 2007; Gulley et al., 2016) and soil storage is typically minimal compared to overall precipitation and ET ($<10 \text{ cm}$) (Crump and Gamble, 2002). For small islands, the volume of potential storage for freshwater is already low, so when the primary controls (P and ET) change, the amount of water available in the lens can drastically change as well. Precipitation reduction because of El Nino Southern Oscillation (ENSO) cycles has been shown to cause devastating droughts on Pacific atolls causing significant freshwater lens depletion (Bailey et al., 2009; Bailey et al., 2010). Droughts are especially problematic as the freshwater lens is commonly pumped as rainwater from catchments is limited during these times (Presley 2005). Furthermore, freshwater lenses in small islands are typically contained within carbonate/coralline and volcanic aquifer material, which are highly permeable aquifer systems. The high permeabilities allow for rapid infiltration, but also rapid exfiltration which makes contemporary climate a dominating force controlling water availability (Vacher, 1988). Pumping further exacerbates water availability via up-coning causing saltwater intrusion. Future climate

^{*} Corresponding author.

E-mail address: pdsPELLM@usf.edu (P. Spellman).

<https://doi.org/10.1016/j.jhydrol.2021.126178>

Received 23 November 2020; Accepted 7 March 2021

Available online 16 March 2021

0022-1694/© 2021 Elsevier B.V. All rights reserved.

projections show that precipitation and for ET variability and magnitude will shift, and thus small island freshwater stores remain some of the most vulnerable to climate change.

In the Bahamas, freshwater resources are already limited and stressed (Roebuck et al., 2004; Diamond and Melesse, 2016) therefore, changes to the primary controls on freshwater availability further exacerbate local water shortages. Over 80% of residents in the Bahamas rely on groundwater pumping from the local freshwater lens while some islands rely on water barged from islands with ample freshwater (e.g. Andros to New Providence) (Roebuck et al., 2004). Therefore, reductions of freshwater stores would have far reaching consequences beyond a single island. The Bahamas is particularly vulnerable as most of the island chain is comprised of low-lying carbonates where the freshwater lens is close to the surface, making it susceptible to contamination (Westcoat & White, 2008). More persistent and permanent changes to the climate will only exacerbate any existing water resource shortages, driving changes in hydrologic and economic sustainability.

Herein, we examine the spatial and temporal changes in freshwater availability across the Bahamian Archipelago using satellite derived precipitation, temperature and evapotranspiration to analyze water budget changes and seasonal shifts in climate parameters. For actual Evapotranspiration (ET_a) changes are compared to global ET_a and land surface temperatures to characterize how key variables in Bahamian water resources are changing with respect to the global averages.

2. Methods

2.1. Site characteristics and selection

The Bahamian Archipelago contains over 700 islands ranging in length from a few to over 100 km. These islands comprise greater than 3000 km² of low-lying carbonate islands, which are susceptible to abrupt declines in freshwater resources seasonally and from hydrological drought conditions (Bailey et al., 2014).

The Bahamian Archipelago was divided into three regions: north, central and south (Fig. 1). The regional division is based on the established climate gradient, differences in observed vegetation, and each regional island's impact from continental fronts and ocean currents (Whitaker and Smart 1997). The northern region, including Grand Bahama and Abaco, historically received greater rainfall than the rest of The Bahamas with averages of about 1300–1400 mm/yr (Roebuck et al., 2004). The higher rainfall can cause islands with traditionally negative water budgets to have positive annual water budgets when hurricanes and large storms pass over the islands. The defined delineation between north and central Bahamas is somewhat arbitrary due to lack of long-term data for many out-islands. However, a delineation was made based on historical approximations to water budgets throughout the island chain (Whitaker and Smart, 1997) along with vegetation and ocean current effects. Vegetation on New Providence and Andros are similar to that of Grand Bahama and Abaco, however rainfall is much closer to that of more southerly islands and potential ET on New Providence has been estimated to be up to 1500 mm/yr. These values make the water budget consistently more negative, which we characterized as representing the central islands. Rainfall on islands in the central region average around 1100 mm/yr. The southern islands, including Great

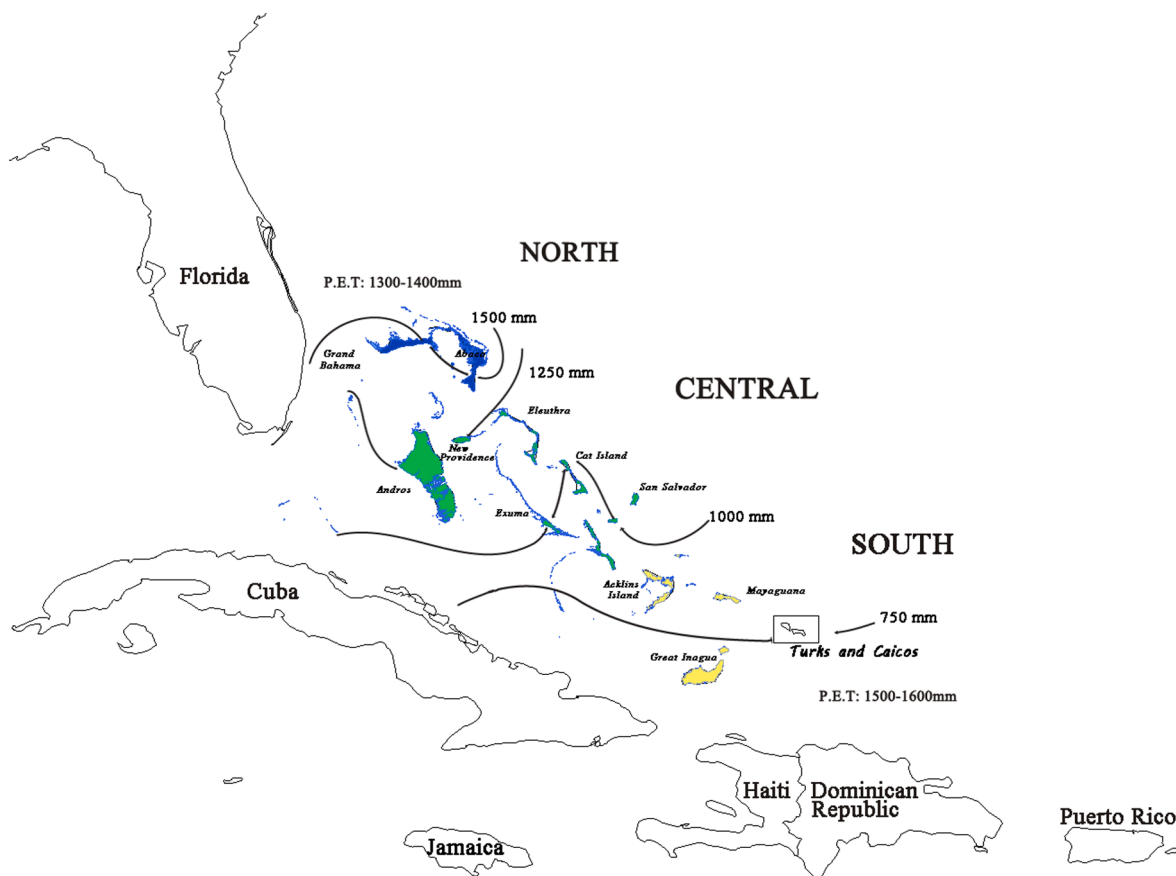


Fig. 1. Location of Bahamian Archipelago in the Caribbean. Figure includes climate gradient (PET and precipitation), as well as identifying select islands and delineations for analysis. Climate gradient for precipitation (isolines) are shown as well as potential ET in the north and south.

Inagua, Mayaguana and Crooked Island have consistent negative water budgets with historically high potential ET upwards of 1500 mm/year and rainfall on average of around 750 mm/yr ensuring these islands almost always have a negative water budget.

3. Data descriptions

3.1. Precipitation and temperature

Monthly cumulative precipitation and maximum and minimum temperatures were obtained via Google Earth Engine (GEE) from the TerraClimate dataset (<http://www.climatologylab.org/terraclimate.html>) (Abatzoglou et al., 2018). The TerraClimate is an merged climate dataset compiled using WorldClim Version 2 (V2) global monthly climate normals which is converted to a monthly timeseries using the Japanese 55-year Reanalysis Product (JRA-55) and Climate Research Unit 4.0 (CRU4.0) gridded data. WorldClim V2 data is a gridded climate dataset that uses remotely sensed Moderate Resolution Infrared Spectroradiometer (MODIS) land surface temperature (max and min) and cloud cover to spatially interpolate climate variables between ground-based climate stations producing a 0.05° (~4.65 km) spatial resolution gridded dataset. To produce time series climate products from the WorldClim V2 monthly normals, the JRA-55 and CRU4.0 gridded datasets are used to climatologically interpolate WorldClim V2 climate normals to time series using monthly climate anomalies. The use of two separate datasets for temporal expansion is done to gain complete global coverage, as CRU4.0 does not include island states or Antarctica. The resulting TerraClimate dataset is a monthly time series of climate variables that includes cumulative precipitation, maximum and minimum temperatures, along with average solar radiation, vapor pressure and wind speed. The combination of data from these sources that make use of ground-based climate stations and satellite products make the TerraClimate dataset a robust time series that has been rigorously validated and shown to perform exceptionally well (Abatzoglou et al., 2018).

3.2. Evapotranspiration

Monthly total actual ET (ET_a) was retrieved via GEE from the results of the Penman-Monteith-Leuning Version 2 (PML_V2) terrestrial ET model. The PML_V2 ET model generates a 500 m, 8-day resolution product that partitions the different components of ET including canopy interception, transpiration from plants, soil evaporation and direct evaporation of water. The utility of the partitioning of ET_a allows hydrologists to analyze which parts of ET are experiencing changes, which can help determine causes of ET_a shifts (i.e. land use changes, soil storage changes, water availability, etc).

PML_V2 estimates ET_a components globally using a combination of reanalysis data (temperature, wind speed, vapor pressure, solar radiation and relative humidity) from the Global Land Data Assimilation System (GLDAS) Version 2.1 and satellite products MODIS Leaf Area Index (LAI), shortwave albedo and emissivity. These data are used to estimate the parameters of the Penman-Monteith-Leuning ET model which is a modified version of the Penman-Monteith equation that includes an additional surface conductance model (Leuning et al., 2015).

The ET_a results of the PML_V2 model have been validated using in situ eddy covariance flux tower measurements across a wide variety of landscapes including tropical forests which are common in the Bahamas; particularly south of Abaco (Henry, 1974). Validation of the individual components of ET involved checking the data to other satellite derived products and field experiments. The PML_V2 model is entirely driven by data that can be obtained via GEE. We therefore selected the PML_V2 model because it was a more robust and rigorously validated ET_a dataset, which was preferred. Further information about calibration and validation of the PML_V2 model can be found in Zhang et al. (2019).

TerraClimate also provides an ET_a product, however, ET_a from TerraClimate has not been as rigorously validated and, where it was

validated, performance was poorer than other products (Abatzoglou et al., 2018). Therefore, we sought to obtain ET_a from a different product (PML_V2 model) with more robust validation and better performance.

3.3. Data acquisition

The most recent TerraClimate dataset contains monthly cumulative precipitation and monthly maximum and minimum temperatures available from 1960 to 2017, but ET_a from PML_V2 was only available from 1/2002–1/2017. Therefore, all variables (precipitation, temperatures and ET_a) were analyzed for water budget analyses from the time-frame between 1/2002–1/2017 ($n = 16$ full years, 204 months). However, validation of precipitation and temperatures along with change point detection utilized the whole time period (1960–2017) available from TerraClimate dataset which was compared to available ground based climate data (see Data Validation hereafter). Data acquisition involved all variables - monthly values of cumulative precipitation, maximum and minimum temperatures, ET_a - averaged over each region using GEE to produce the regional value. Averaging over each region (north, central, south) was done by outlining the regions within GEE using polygons and taking the mathematical averages of the pixels in each region that contained land.

3.4. Data validation

Though the previous datasets (TerraClimate and PML_V2) have been externally validated, internal validation was performed to ensure that no unreasonable or extreme values were obtained which would affect analysis.

We evaluated the performance of the TerraClimate precipitation and maximum and minimum temperatures by comparing it to observed data where available. We obtained precipitation and maximum and minimum temperature data from a collection of sources (Table 1) including www.climate-data.org for available islands, literature sources (Whitaker and Smart, 1997), and Bahamas Meteorological Ministry (email).

For each region, the observed precipitation and minimum and maximum temperature data were averaged over the islands that fell within each region and compared to the TerraClimate variables. All data were compared as annual averages, as these were the easiest to obtain observed values for a larger set of islands. Data that was not retrieved as annual averages were aggregated to annual values.

Validation of ET_a was not directly comparable as no direct estimates of ET_a have been made available on the islands; only potential ET has been estimated. However, upon comparisons of climate gradients of potential ET established by previous researchers (Whitaker and Smart, 1997; Martin et al., 2012), the ET_a values obtained were less than potential ET values reported, which was the best validation that could currently be achieved.

Table 1

Data source description for validation. BMM = Bahamas Meteorological Ministry, CD = climate-data.org, L = literature source, Whitaker and Smart, 1997.

REGION	ISLAND	SOURCE	TIMEFRAME
NORTH	Grand Bahama	BMM	1985–2015
	Abaco	CD/L	1990–Present
CENTRAL	New Providence	BMM	1985–2015
	San Salvador	BMM/Local Weather station	1985–Present
	Long Island	CD	1990–Present
	Exuma	BMM	1985–2015
SOUTH	Mayaguana	BMM	1985–2015
	Great Iguana	BMM	1985–2017
	Crooked Island	CD/L	1990–Present

3.5. Data analysis

3.5.1. Detecting trends and underlying structure

Trends in time series were determined using Locally Weighted Estimated Scatterplot Smoothing (LOWESS) which is a common local regression technique employed to smooth data and emphasize underlying structure in time series (Moran, 1984; Hirsch et al., 1991). LOWESS involves fitting low order polynomials (typically linear or quadratic) to continuous, windowed subsets of the data whereby at each point in time is estimated using robust weighted least squares regression (Equation (1)).

$$\hat{y}_i = b_0 + b_1 x_i + b_2 x_i^2 \quad (1)$$

Parameter estimates $\{b_0, b_1, b_2\}$ are performed using weighted least squares fitting methods whereby the weighted ($w(d)$) sum of squared residuals $((y_i - \hat{y}_i)^2)$ on the windowed data $(-k, k)$ is minimized (Eq. (2)).

$$\sum_{-k,k}^n w(d)(y_i - \hat{y}_i)^2 \quad (2)$$

The weighting function initially applied is tri-cubic (Eq. (3a)), however if there are any large residuals that would be considered outliers, a bi-cubic weighting function (Eq. (3b)) is applied and the local fit is repeated.

$$w(d) = \begin{cases} (1 - |d|^3)^3 & \text{for } 0 \leq |d| < 1 \\ 0 & \text{otherwise} \end{cases} \quad (3a)$$

$$w(d) = \begin{cases} (1 - |d|^2)^2 & \text{for } 0 \leq |d| < 1 \\ 0 & \text{otherwise} \end{cases} \quad (3b)$$

$$d = \frac{(x_0 - x_i)}{\max(|x_0 - x_i|)} \quad (3c)$$

The degree of windowing allows for estimation of d (Eq. (3c)), where a fraction of the dataset is contained within each window ($integer(k = \alpha n + 0.5)$) and used for local fitting. The span (α) of the window is initially set through either a trial and error approach, informed selection or simulation. Herein, because of the small sample size (<30), simulations were performed that used a robust Akaike Information Criteria (AIC) to determine the optimal weighted smoothing parameter α for each region (Sharma et al., 2015). Estimation of α involved simulating 500 realizations spanning an α range uniformly distributed from 0.01 to 1 and calculating the AIC for each simulation. The smallest AIC was used to determine the appropriate α value for each of the three regions.

LOWESS trends are particularly useful in smaller sample sizes as they can emphasize structure and trends that ordinarily are not picked up within a statistical test that relies on variance for a small sample (Hirsch et al., 1991). The drawback to LOWESS in small samples is it can highlight structure that may be well within the bounds of the natural variability of the dataset. Therefore, careful weighting and interpretation is needed when assessing the significance of the result.

3.5.2. Detection of change points in seasonal values

Detection of seasonal shifts in ET were done using seasonal precipitation and ET sums and change point analysis of the mean for the developed time series. Monthly ET was summed for the established, contemporary wet (June–November) and dry (December–May) seasons (Cant and Weech 1976; Whitaker and Smart 1997; van Hengstrum et al., 2016) to create a time series of wet and dry season values from 2002 to 2017 ($n = 16$).

To determine when statistically significant changes in ET occurred during each season, change points where detected using sequential Mann-Kendall (seqMK) trend test at the 5% significance level. The seqMK test is specifically used to estimate abrupt changes in the mean of time series. The seqMK is an extension of Mann-Kendall trend test which is used to detect monotonic trends in data whereby the seqMK test ex-

tends those same methods, determining the breakpoint when that monotonic trend occurs. The analysis is done by using both a progressive ($u(t)$) and regressive ($u'(t)$) analysis of the time series, whereby when the progressive and regressive series cross each other and then diverge beyond a threshold, a change point occurs. Each series, $u(t)$ and $u'(t)$, are standardized with a zero mean and unit standard deviation. To set up the progressive and regressive series, first the magnitudes of x_j annual mean time series ($j = 1, \dots, n$) are compared with x_k , $k = 1, \dots, j - 1$. The number of cases where $x_j > x_k$ is counted and denoted by n_j at each comparison. The test statistic is given in Eq. (4) and the mean and variance of the test statistic in Eqs. (5) and (6) respectively.

$$t_j = \sum_{k=1}^j n_j \quad (4)$$

$$E[t_j] = \frac{j(j-1)}{4} \quad (5)$$

$$Var[t_j] = \frac{j(j-1)(2j+5)}{72} \quad (6)$$

The sequential values of the progressive series are calculated using Eq. (7).

$$u(t) = \frac{t_j - E[t_j]}{\sqrt{Var[t_j]}} \quad (7)$$

The same methods are used to setup the regressive series, $u'(t)$, and both are compared (plotted) and values that are equal at time (t) and subsequently diverge at a threshold exceeding the confidence level of $+/-1.96$ ($\alpha = 0.05$) are significant change points.

Because the seqMK does a sequencing of progressive (forward) and regressive (backward) series, multiple change points may be detected and for the purposes herein, the most significant change point in terms of magnitude of change was selected as the change point of interest.

Using the years established as a change point in the ET dataset, the precipitation data were split at that change point and significant differences in the mean in precipitation before and after were tested using the Welch's t -test with unequal variances at $\alpha = 0.05$ significance level. Because the dataset for comparison of means would be small (yearly sums for each season at $n = 15$), the power of the test would be low indicating that the probability of finding a statistically significant result. Therefore, to complement the results of the t -test, LOWESS trends were also performed on each data series to help validate the results.

3.5.3. Comparison to global temperature anomalies and ET changes

The changes in ET_a within each region and across the Bahamas were compared to changes in global land surface temperatures (gLST's) and global ET_a changes. gLST's are used to monitor changing land cover dynamics as well as overall water budget and ecological stresses. gLST's record how incoming solar radiation interacts with the land surface, making it a reliable indicator of energy changes at the land surface-atmosphere boundary and a key variable in ET_a estimation (Oliviera-Guerra et al., 2017). gLST's monitor overall changing global dynamics thus taking the pulse of global climate change and have been tracked for a much larger time frame than global ET_a .

We obtained gLST anomalies from NASA's Near Earth Observatory (NEO) data repository (<https://neo.sci.gsfc.nasa.gov/>). The original gLST's are recorded at 8-day, 500 m spatial resolution from MODIS aboard NASA's Terra satellite. The climatology used to produce the gLST anomalies is the baseline period from 2001 to 2010.

Because of a lack of long-term record of ET_a , ET_a across the Bahamas was compared both to gLST's and the global ET_a data that was available. To estimate ET_a anomalies, the baseline ET_a was taken to be the average for the dataset from 2002 to 2010 as it most directly compared to the timeframe of gLST anomaly baseline. The same smoothing technique using LOWESS was employed as in previous analyses. The comparison of

local ET_a to both global ET_a and gLST's gives a comparative approximation of changes at local and regional scales.

4. Results

4.1. Data validation and description

Climate variables for the available time periods matched well with observed historical data (Figs. 2 and 3). Estimated annual precipitation was 1339 mm/yr from the TerraClimate precipitation dataset which is slightly less than annual averages of 1500 mm/yr for Grand Bahama and Andros. The discrepancy is likely due to a few factors. First, intense hurricane rainfall may not have been captured in the TerraClimate data. Second, the northern island delineation also consisted of the Berry Islands which is closer to New Providence which receives about 1200 mm/yr and thus, the inclusion of these islands into the northern Bahamas regional delineation could drive the annual average down. Years where hurricanes pass over the islands can significantly increase overall precipitation which drives up annual averages over 1500 mm/yr. For example, in 2019, Dorian passed over the northern Bahamas (Andros and Grand Bahama) and resulted in an additional 900 + mm of rainfall in 4 days, significantly driving up annual totals (weather.com). Average annual precipitation totals for the central Bahamas were also well matched, falling within the ranges of reported precipitation values for the islands included in the central delineation (Table 2). Average annual precipitation was estimated to be 813 mm/yr for the south islands which include Inagua and Mayaguana where average annual precipitation is reported to be roughly 750–800 mm/yr. The inclusion of some more northerly islands such as Crooked Island and Cat Island in the southern delineation could slightly increase the average annual totals. Maximum and minimum temperatures for the northern, central, southern and overall Bahamas were relatively well matched to observed temperatures, with some slight deviations due to the selected delineations.

4.2. Spatial and temporal water budget changes

Seasonal change point detection using the seqMK test showed significant upward change points in ET_a for most regions and across the Bahamas in both wet and dry seasons except for the south in the wet season (Table 3). The change points occurred around 2008–2009 for the wet season and from 2009 to 2013 for the dry season. All changes are amplified by the LOWESS lines which show a continuous increase in ET_a for the central Bahamas in both wet and dry seasons (Fig. 4). Slight dips are observed in the beginning of the series in the LOWESS line likely as a function of the small sample size.

LOWESS lines and overall volumes of precipitation (Fig. 4) indicate some upward and downward trends within each season. It should be noted that the average annual calculations for the pre-change point precipitation considered all years from 1960 up until the change point. Though no significant change occurred outside the range of variability for the data, any decreasing or increasing trends within the dataset can make a significant difference in the amount of available water for the season and ultimately the water year. Significant trends mostly occur in the central and southern Bahamas, where in the wet season, decreases in precipitation have been occurring while ET_a increases, which is likely temperature driven. This opposite trend is seen in the dry season where slight increases in precipitation are observed with coincident increases in ET_a , which is likely driven by increases in water availability. All ET_a increases were due to evaporation from water surfaces for all regions with some statistically significant increases in canopy evaporation for the wet and dry seasons for all regions except the south during the wet season (Fig. 5). The largest increases were observed in water evaporation where with minimal increases in canopy evaporation. No statistically significant changes were seen in evaporation from soil and transpiration in any region.

Overall yearly water availability showed initial reductions but remained stable for the northern and southern Bahamas, but steady declines were observed for the central region (Fig. 6). Though annual water budgets can mask the timing of recharge (see Discussion), they

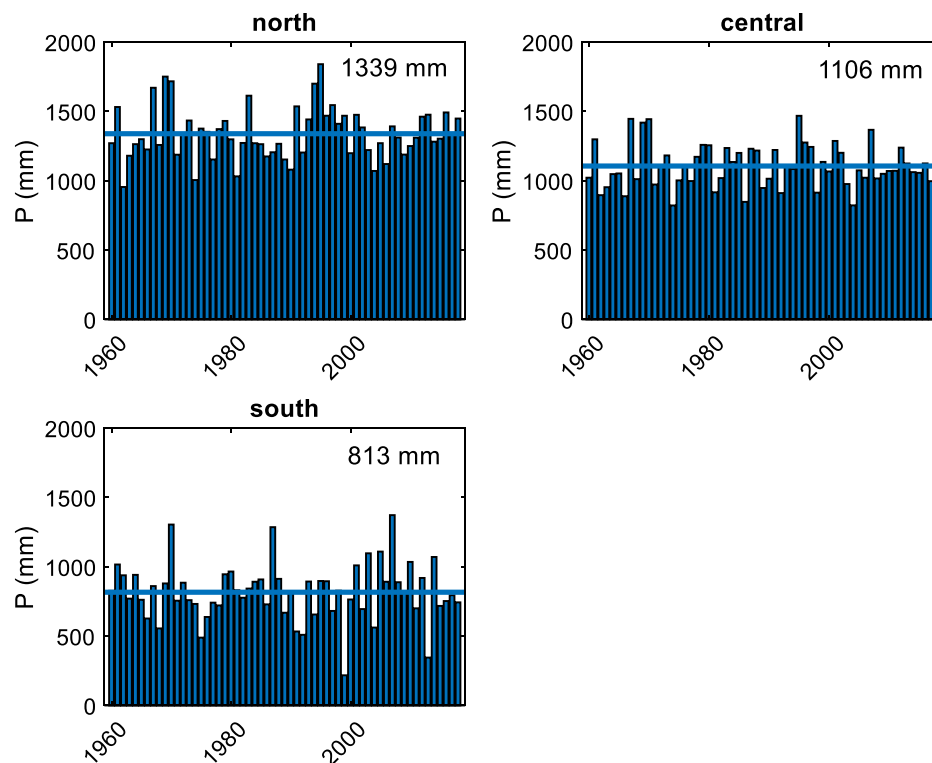


Fig. 2. Regional TerraClimate annual precipitation time series data vs. observed regional long-term average annual precipitation comparisons. Long-term observed regional average value in upper right-hand corner and also plotted as a horizontal line.

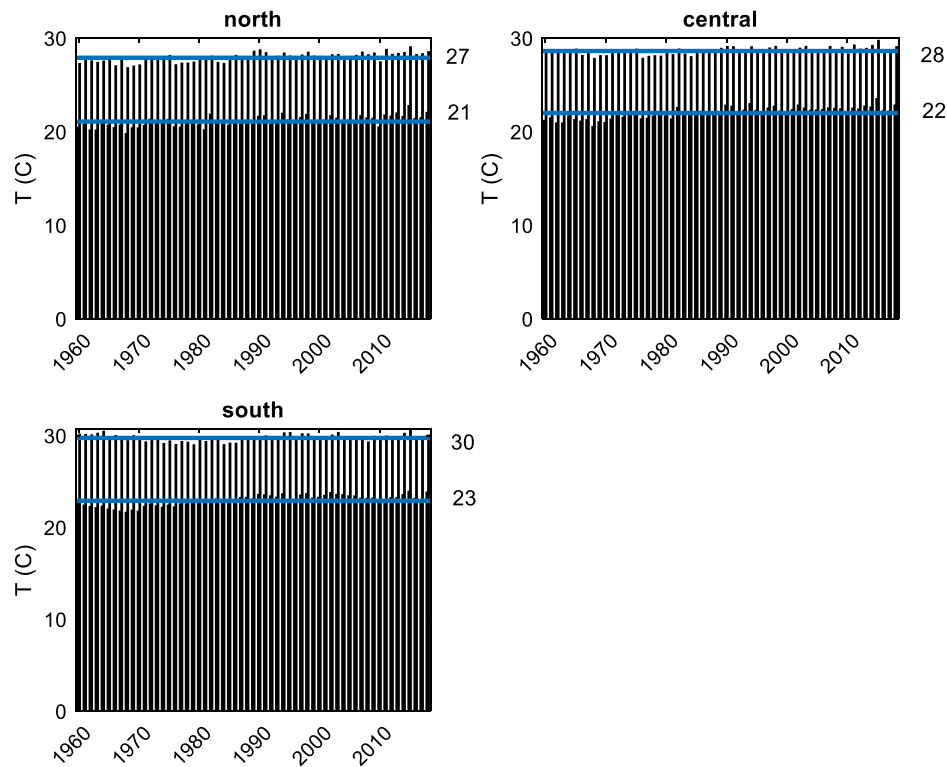


Fig. 3. Regional TerraClimate annual maximum and minimum temperature time series data vs. observed regional long-term average maximum and minimum temperatures comparisons. Long- term observed regional average value in upper right-hand corner and also plotted as a horizontal line.

Table 2

Statistics of satellite derived datasets.

REGION	P			Minimum Temperature			Maximum Temperature			ET			Change Point (Wet)	Change Point (Dry)
	Max (mm/yr)	Min (mm/yr)	Average (mm/yr)	Max (C)	Min (C)	Average (C)	Max (C)	Min (C)	Average (C)	Max (mm/yr)	Min (mm/yr)	Average (mm/yr)		
NORTH	1840	955	1339	22	19	21	29	26	27	1373	1189	1272	2008	2009
CENTRAL	1465	821	1106	23	20	21	29	27	28	1191	926	1064	2009	2011
SOUTH	1372	217	816	23	21	22	30	28	29	1322	1214	1271	2007	2013
ALL	1559	664	1087	23	20	21	29	27	28	1295	1110	1202	2009	2010

Table 3

Wet and dry season changes in Precipitation and overall actual ET and significance of change from *t*-test.

PRECIPITATION								
REGION	WET				DRY			
	BCP (mm)	ACP (mm)	p-value	% CHANGE	BCP (mm)	ACP (mm)	p-value	% CHANGE
NORTH	918.86	898.95	0.40	−2.17%	417.69	451.91	0.64	8.19%
CENTRAL	783.26	747.69	0.84	−4.54%	328.54	336.09	0.27	2.30%
SOUTH	489.25		–	–	331.04	298.55	0.00	−9.81%
ALL	772.84	745.28	0.57	−3.57%	353.33	371.76	0.37	5.22%
ET								
REGION	WET				DRY			
	BCP (mm)	ACP (mm)	p-value	% CHANGE	BCP (mm)	ACP (mm)	p-value	% CHANGE
NORTH	793.77	871.60	0.01	9.80%	660.39	696.20	0.00	5.42%
CENTRAL	689.59	789.64	0.00	14.51%	469.33	562.63	0.00	19.88%
SOUTH	829.79		–	–	683.63	713.89	0.00	4.43%
ALL	720.78	808.10	0.00	12.11%	523.00	594.56	0.00	13.68%

provide a good indication of overall water availability and thus, are commonly used as indicators of overall island aridity (Vacher and Wallis 1992). The annual P-ET values show a significant uptick in 2007 for the

central and southern Bahamas, which came from a particularly devastating tropical system (Noel) that passed slowly over this region of the archipelago. Noel likely added an additional 400 mm of rain for that

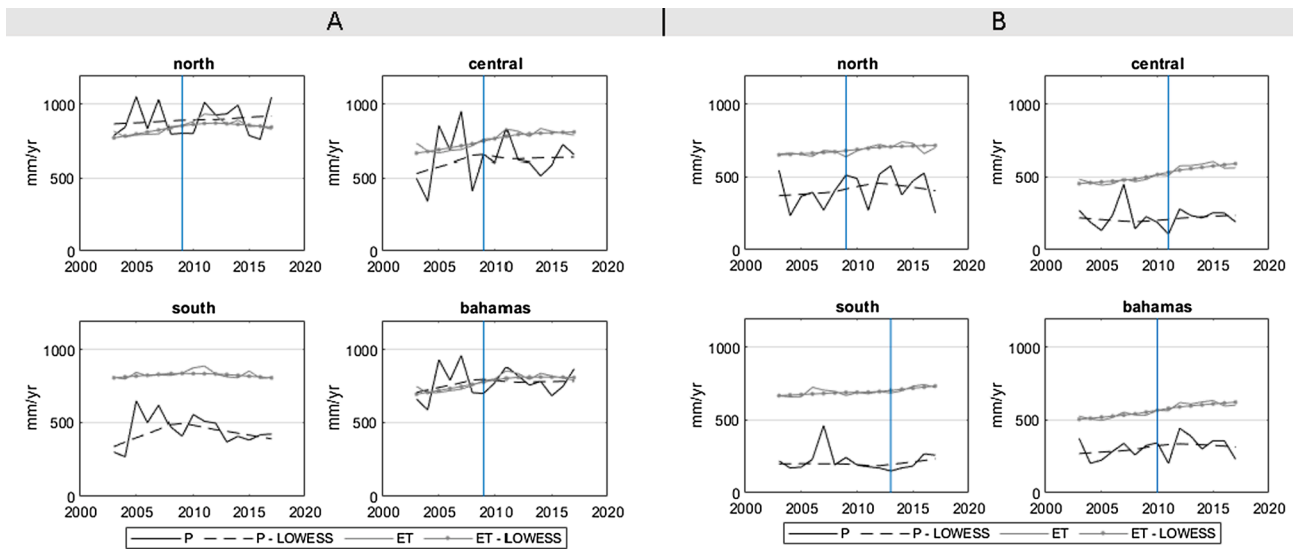


Fig. 4. Seasonal time series of precipitation and total evapotranspiration (ET_a) for established (A) wet and (B) dry seasons. LOWESS line indicates trend of decreasing or increasing patterns in each pre-defined season and associated vertical line denotes year when change point was detected for the ET_a data series.

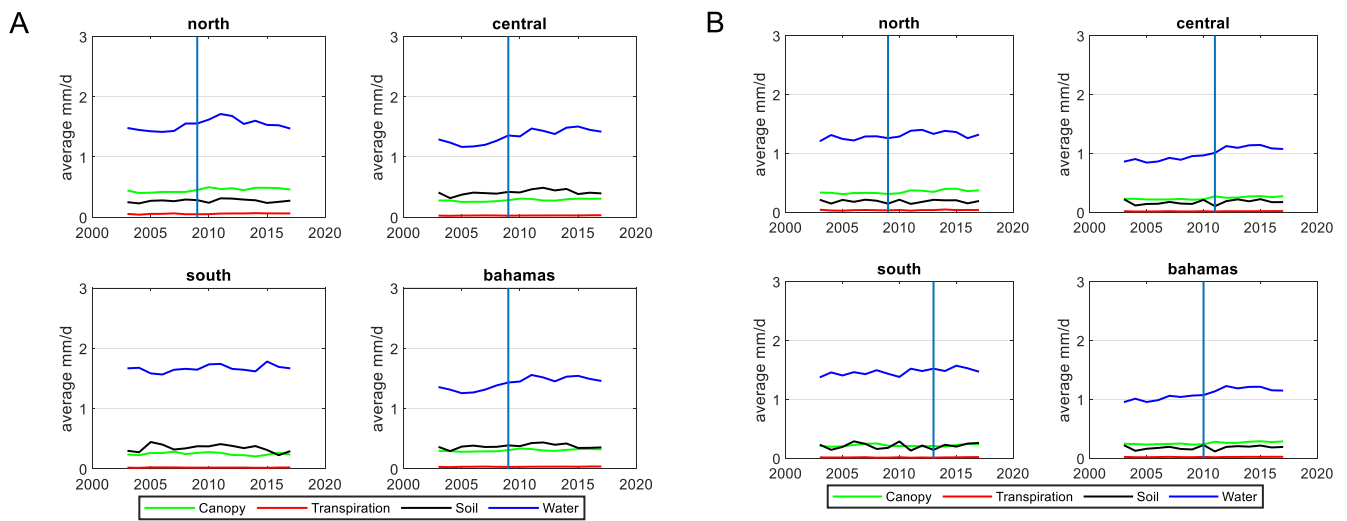


Fig. 5. Seasonal shifts in components of ET_a for established (A) wet and (B) dry seasons. Vertical line denotes year change point was detected (if significant) in the overall ET_a data series (change point same as Fig. 4).

year, which may have influenced the LOWESS trend lines resulting in upticks followed by downward trends in the central Bahamas. However, even removing the rainfall amount contributed by Noel in 2007, the central portion of the Bahamas would have still had a more positive water balance than in recent years.

4.3. Bahamian ET_a trends relative to global anomalies

Trends in ET_a across the Bahamas match or exceed rates of global ET_a (Fig. 7). ET_a across the whole Bahamas, specifically the northern and southern regions, are similar to the rate of global increases in ET_a . The central region, however, shows increasing ET_a higher than global rates. Global ET_a trends also show a breakpoint around 2009, which is coincident with dry season increases in ET_a for the Bahamas which saw significant ET_a increases between 2008 and 2009 followed by increases in ET_a during the dry season around 2010. The comparison of ET_a changes with respect to gLST's indicates that increases in ET_a is not entirely temperature driven, but likely due to shifts in precipitation patterns which can drive higher or lower ET_a depending on water

availability changes.

5. Discussion

Young carbonate platforms that form The Bahamian Archipelago are characterized by high matrix porosity and permeability because it has not yet undergone significant diagenetic processes (Ford and Williams, 2013; Gulley et al., 2013). The high permeability of the Bahamian Islands accelerates rainfall infiltration at the land surface causing a lack of surface water, with the exception of blue holes or topographically low surface areas that are filled with water from raised water tables that are influenced by sea level fluctuations (Martin et al., 2013; Gulley et al., 2012). The lakes that exist are typically brackish to hypersaline waters due to high potential ET rates exceeding rainfall (Whitaker and Smart, 2007; Vacher and Wallis, 1992). Along with limited surface waters, the lack of surface drainage and little to negligible runoff to depressional lakes supports using P-ET as an approximation of effective recharge in the water budget which has been assumed by other water resource studies in the region (Vacher and Wallis, 1992; Gulley et al., 2016).

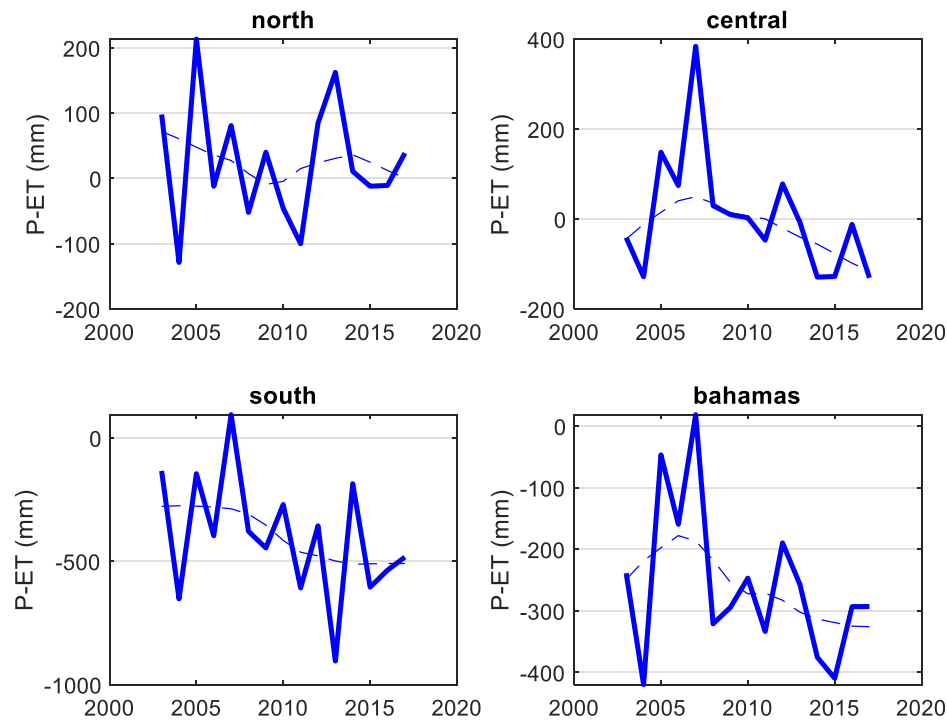


Fig. 6. Annual water availability (P-ET) trends across the Bahamas.

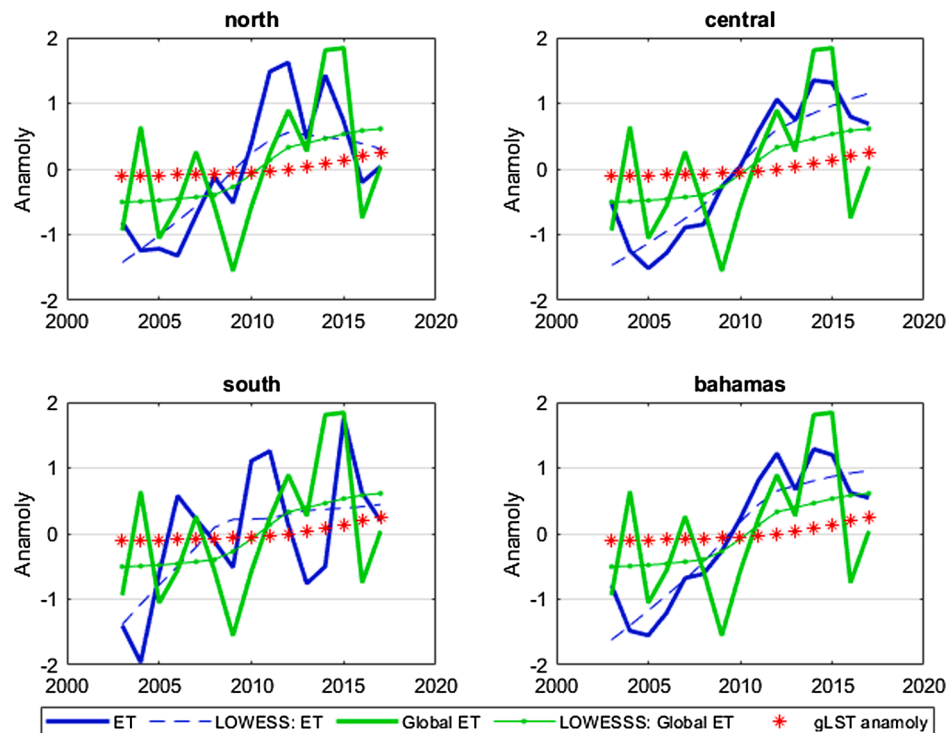


Fig. 7. ET anomaly (ET – mean ET) trends vs. global anomaly in global land surface temperatures (gLST).

Current and historical periods of increasing aridity in the Bahamas have been noted and likely are a result of changes in ocean and atmospheric circulation. One of the more intense historical hydrological droughts occurred in the Holocene between 3300 and 2500 years B.P. The Holocene drought was marked by significant changes in water budgets in the northern Bahamas as evidenced from lake cores in Abaco (van Hengstrum et al., 2016). Increases in marine tolerant ostracodes were observed which would have coincided with increases in salinity.

The drought was likely caused by decreasing precipitation due to a southward or westward expansion of the North Atlantic Subtropical High (NASH) as a result of southern Intertropical Convergence Zone (ITCZ) displacement. Modern analogues validate this claim, as the Yucatan experiences a climate gradient that has been definitively linked to displacement of the ITCZ on seasonal and decadal time scales. Furthermore, recent Caribbean dry period from 1979 to 1989 was preceded by intensification of the NASH. Our contemporary analysis of

increasing drought conditions mirrors results showing increasing aridity between 2013 and 2016 spanning over Cuba and the Antilles (Herrera et al. 2016). Our results confirm that a drought is indeed occurring, though our changes to aridity were slightly earlier than 2013.

As global warming intensifies, changing atmospheric and subsequent ocean circulation will continue to change (Wattmeier and Friarson, 2018). Amplified warming in the upper tropical troposphere can cause temperature gradients to increase from equator to pole, resulting in Hadley cell edge expansion. The Hadley cell expansion causes alterations to the ITCZ which may cause disruptions in water budgets across the Bahamian Archipelago. A small shift in the ITCZ northward could cause an increase in precipitation and hurricane development within the Bahamian Archipelago. However, a large shift northward of the ITCZ can cause the zone of regional subsistence to change and cause a decrease in precipitation along the entire Bahamian Archipelago, causing the area to trend towards an increasingly arid climate. Because the Bahamas, particularly the north, are close to the contemporary edge of the Hadley Cell, it is likely more sensitive to changes in Hadley Cell circulation than elsewhere along the Caribbean. With the warming of the subtropical landmasses seen in the early Holocene, and possibly in the future with anthropogenic forced warming, the ITCZ could be drawn even more northward than seen in the recent past, impacting the evaporation-precipitation balance of the Archipelago (Arbuszewski et al., 2013).

As continental fronts across North America increase in intensity and change in their frequency, changes in water budgets may result that we cannot anticipate. The Bahamian Archipelago being the closest of the Caribbean Islands to the subtropical jet stream, are more impacted by the variation of the El Niño-Southern Oscillation (ENSO) more so than the North Atlantic Oscillation (NAO) which impact lower latitudes of the Caribbean (Jury et al., 2007). During El Niño, or warm phase of ENSO, the subtropical jet stream strengthens and shifts south in the Atlantic and overall Atlantic hurricane activity is reduced (Gray, 1984). During La Niña, or cold phases of ENSO, along with neutral ENSO phases, the opposite occurs and overall hurricane activity, and precipitation will be increased in the Atlantic (O'Brien et al., 1996). These hurricanes and precipitation patterns will be more impacted by the onset of a new ENSO phase in October, than the decaying of a previous phase (Tartaglione et al., 2003). The predictability of ENSO phases has improved substantially, and the predictability of the precipitation in North America during the hemispherical winter will be linked to the current ENSO phase, but the influences of different phases will be non-linear, and predicted patterns may not be precisely reflected in actual precipitation patterns (Li et al., 2019). The impact of ENSO is often limited to locations found closer to the northern edge of the Hadley cell and therefore the subtropical jet streams (Jury et al., 2007). Thus, further analysis of other extremes and climatic shifts in other island settings would be warranted.

The seasonal shift in precipitation from wet to dry season and consistent increase in ET_a provide insight into how overall yearly water availability is changing and driving increasing aridity. Most recharge to the freshwater lens occurs during the wet season when intense and steady rainfalls drive infiltration after an island specific recharge threshold (Little et al., 1973; Budd 1984; Jones and Banner 2003); though rapid infiltration through roots and solution holes occur during most rainfall events (Myroie and Carew 1995). During the dry season, rains are shorter and less intense which does not drive as much recharge into the freshwater lens, leaving water to pond on the surface longer, whereby much of the water can be evaporated. ET_a is also lower than in dry season months primarily due to cooler temperatures. The slight shift in precipitation seasonality coupled with an overall downward trend when accounting for hurricanes (Roebuck et al., 2004) simultaneous with increasing ET_a suggest that water resource availability is on a negative trajectory.

The significance of increased evaporation directly from water also has implications for the freshwater lens dynamics and viability (Gulley et al., 2016). Lakes, blue holes and wetlands on The Bahamas are

persistent features of the karst landscape, segmenting the freshwater lens creating hydraulic lows that focus freshwater gradients (Martin et al., 2012). As increases in water evaporation occur from these lakes, further thinning and segmentation of the freshwater lens occurs, driving more brackish aquifer conditions and depleting water resource faster than sea level rise. The impacts of freshwater lens volume as a function of evapotranspiration have shown that the depletion of freshwater lens stores is a linear function of ET_a and thus, increases in ET_a directly affect existing freshwater stores. Thus, freshwater depletion is not only a function of reduced water availability, but also from direct evaporation from the freshwater lens that occurs more readily (Gulley et al., 2016). Therefore, increasing aridity not only reduces incoming available water, but also more rapidly depletes existing freshwater.

Though definitively linking the change in water budgets through the Bahamas to anthropogenic causes is difficult given limited data to estimate long-term, ET_a from the islands, analyzing both global ET_a and gLST anomalies in comparison with local averages across The Bahamas gives some insight into a potential link. Previous comparisons with contemporary episodes of aridity in the Bahamas illustrate that the current trends may be more consequential as evidenced by increasing temperatures locally and globally (Fig. 7). However, in regions where shifting ocean currents and sea surface temperatures have a profound impact on climate from year to year such as The Bahamas, these areas may experience exacerbated effects as ocean currents temper variability in land surface and air temperatures, resulting in compound heating effects. The increasing ET_a trend in some areas of the Bahamas, particularly the central region, observed in the last decade shows a rate that may be greater than global averages. This indicates depletion of freshwater stores may occur more rapidly in small islands requiring more focus on changing water budget components.

Though ET_a and precipitation generated using satellite data at the regional scale has been shown to be reliable, analyzing island scale water budgets inherently produces greater uncertainty. We aggregated regional data to produce regional analysis of water budgets based on climatic gradients and land surface dynamics, however each island would be unique and have its own singular water management issues. Therefore, further analyses on water budgets at the island scale should consider ground truthing ET_a and precipitation, as necessary.

6. Conclusions

We used satellite guided reanalysis precipitation and satellite derived ET_a to analyze trends in P-ET which is a fundamental control on island freshwater stores. We found that increases in ET_a are a result of increases in temperature, but also likely due to shifting precipitation which increases in water availability. As climate change in The Bahamas is historically been related to changes in Hadley Cell circulation patterns, recent evidence suggests this could be a cause of aridity changes. Furthermore, it was shown that ET_a throughout The Bahamian Archipelago chain is increasing at a rate higher than global average ET_a , which may put the islands at a greater risk for water sustainability when compared to continental settings which are less influenced by ocean currents and marine conditions. As tropical islands have a more tempered climate, baseline land surface and water temperatures which affect ET_a rates are not as variable and could therefore be a cause of exacerbated ET_a in these island states.

Key findings

- Consistent with global trends, ET is increasing across the Bahamas but at a higher rate, particularly the central and southern regions
- Cause of increasing ET are likely driven by both increases in temperature and an increase in precipitation in the dry season and reduction of precipitation in the wet season, reducing water available for recharge, increasing overall water available for ET
- Majority of increases in ET are due to direct water evaporation, which has implications for freshwater lens thinning

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Arbuszewski, J.A., deMenocal, P.B., Cléroux, C., Bradtmiller, L., Mix, A., 2013. Meridional shifts of the Atlantic intertropical convergence zone since the Last Glacial Maximum. *Nat. Geosci.* 6 (11), 959–962.
- Bailey, R.T., Jenson, J.W., Olsen, A.E., 2010. Estimating the ground water resources of atoll islands. *Water* 2 (1), 1–27.
- Budd, D.A., Vacher, H.L., 1991. Predicting the thickness of fresh-water lenses in carbonate paleo-islands. *J. Sediment. Res.* 61 (1), 43–53.
- Crump, M.A., Gamble, D.W., 2002. Climate-derived water budget and synoptic-scale precipitation pattern analysis. Proceedings of the 11th Symposium on the Geology of the Bahamas and other Carbonate Regions.
- Diamond, M.G., Melesse, A.M., 2016. Water resources assessment and geographic information system (GIS)-based stormwater runoff estimates for artificial recharge of freshwater aquifers in New Providence, Bahamas. In: *Landscape Dynamics, Soils and Hydrological Processes in Varied Climates*. Springer, Cham, pp. 411–434.
- Falkland, A., Custodio, E., 1991. Hydrology and water resources of small islands: a practical guide: a contribution to the International Hydrological Programme. *Stud. Rep. Hydrol.* 49, pp. i–xiii.
- Ford, D., Williams, P.D., 2013. *Karst Hydrogeology and Geomorphology*. John Wiley & Sons.
- Gray, W.M., 1984. Atlantic seasonal hurricane frequency. Part II: forecasting its variability. *Mon. Weather Rev.* 112 (9), 1669–1683.
- Gulley, J.D., Martin, J.B., Moore, P.J., Murphy, J., 2013. Formation of phreatic caves in an eogenetic karst aquifer by CO₂ enrichment at lower water tables and subsequent flooding by sea level rise. *Earth Surf. Process Landforms* 38, 1210–1224.
- Gulley, J.D., Martin, J.B., Spellman, P., Moore, P.J., Screaton, E.J., 2012. Influence of partial confinement and Holocene river formation on groundwater flow and dissolution in the Florida carbonate platform. *Hydrol. Process.* 28, 705–717.
- Gulley, J.D., Mayer, A.S., Martin, J.B., Bedekar, V., 2016. Sea level rise and inundation of island interiors: Assessing impacts of lake formation and evaporation on water resources in arid climates. *Geophys. Res. Lett.* 43 (18), 9712–9719.
- Henry, P.W.T., 1974. The pine forests of the Bahamas.
- Hirsch, R.M., Alexander, R.B., Smith, R.A., 1991. Selection of methods for the detection and estimation of trends in water quality. *Water Resour. Res.* 27 (5), 803–813.
- Holding, S., Allen, D.M., 2014. From days to decades: numerical modeling of freshwater lens response to climate change stressors on small islands. *Hydrol. Earth Syst. Sci. Discuss.* 11, 11439–11487.
- Jones, I.C., Banner, J.L., 2003. Estimating recharge thresholds in tropical karst island aquifers: Barbados, Puerto Rico and Guam. *J. Hydrol.* 278 (1–4), 131–143.
- Jury, M., Malmgren, B.A., Winter, A., 2007. Subregional precipitation climate of the Caribbean and relationships with ENSO and NAO. *J. Geophys. Res.: Atmos.* 112 (D16).
- Li, X., Hu, Z.Z., Liang, P., Zhu, J., 2019. Contrastive influence of ENSO and PNA on variability and predictability of North American winter precipitation. *J. Clim.* 32 (19), 6271–6284.
- Martin, J.B., Gulley, J., Spellman, P., 2012. Tidal pumping of water between Bahamian blue holes, aquifers, and the ocean. *J. Hydrol.* 416, 28–38.
- Moran, G.W., 1984. Locally-Weighted-Regression Scatter-Plot Smoothing (LOWESS): a graphical exploratory data analysis technique. NAVAL POSTGRADUATE SCHOOL MONTEREY CA.
- Myroie, J.E. and Carew, J.L., 1995. Karst development on carbonate islands.
- Presley, T.K., 2005. Effects of the 1998 drought on the freshwater lens in the Laura area, Majuro Atoll, Republic of the Marshall Islands. US Geological Survey.
- Tartaglione, C.A., Smith, S.R., O'Brien, J.J., 2003. ENSO impact on hurricane landfall probabilities for the Caribbean. *J. Clim.* 16 (17), 2925–2931.
- Roebuck, L., Pochatila, J. and Ortiz, T., 2004. Water resources assessment of the Bahamas. US Army Corps of Engineers, Mobile District & Topographic Engineering Center.
- Schneider, J.C., Kruse, S.E., 2003. A comparison of controls on freshwater lens morphology of small carbonate and siliciclastic islands: examples from barrier islands in Florida, USA. *J. Hydrol.* 284 (1–4), 253–269.
- Vacher, H.L., Wallis, T.N., 1992. Comparative hydrogeology of fresh-water lenses of Bermuda and Great Exuma Island, Bahamas. *Groundwater* 30 (1), 15–20.
- van der Velde, M., Javaux, M., Vanclooster, M., Clothier, B.E., 2006. El Niño-Southern Oscillation determines the salinity of the freshwater lens under a coral atoll in the Pacific Ocean. *Geophys. Res. Lett.* 33 (21).
- IPCC, 2014. Climate change 2014: Synthesis report. In R. K. Pachauri & L. A. Meyer (Eds.), (151 pp.) Geneva, Switzerland: IPCC.
- Whitaker, F.F., Smart, P.L., 1997. Hydrogeology of the Bahamian archipelago. In: *Geology and Hydrogeology of Carbonate Islands*. Elsevier, Amsterdam, pp. 183–216.
- Whitaker, F.F., Smart, P.L., 2007. Geochemistry of meteoric diagenesis in carbonate islands of the northern Bahamas: 1. Evidence from field studies. *Hydrol. Process.* 21 (7), 949–966.
- White, I., Falkland, T., 2009. Management of freshwater lenses on small Pacific islands. *Hydrogeol. J.* 18 (1), 227–246.