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Research Article

LONGTIME CHANGES OF THE MARINE ENVIRONMENT AND PROJECTIONS AROUND THE BAHAMAS

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ABSTRACT
The study focuses on the impact of global changes in The Bahamas. The marine environment surrounding The Bahamas is described with satellite derived sea surface temperature, salinity, precipitation and chlorophyll concentrations. The data set used in this study covers a time frame of more than ten years, except for the measurement of sea surface salinity. The observed changes for precipitation and temperature are an indication for larger environmental fluctuations. In particular, interannual sea surface temperature measurements show for all seasons a warming trend although they have a slight difference in slope. Comparing the temperatures from 2010 with those predicted for 2035, it is evident that over a time frame of 25 years, the temperature for all seasons may increase above one degree centigrade. The highest predicted increase is observed for the period September to November with 1.7 °C, while lowest predicted increase is 1.0 °C for June to August. It is evident that the marine environment of The Bahamas is already exposed to a critical scenario related to the global warming trend and, if linear projections for 2035 are valid, sea surface temperature increase in The Bahamas, will surpass the lower limit of global temperature increase as recommended by the Intergovernmental Panel on Climate Change (IPCC).

Keywords: *Bahamas**,** Marine Environmental Changes, Temperature Increase, Projections*

INTRODUCTION

Small islands play a minor role with respect to their emission of greenhouse gases and therefore contribute only marginally to the effects of climate change. However, the islands are already witnessing a negative impact of global change, in particular through the increase of temperature and sea level rise. The risk profile and vulnerability affiliated with the anticipated changes due to global warming differ from island to island, but small islands are left with only few alternatives to mitigate the impact of temperature and sea level increase. Global climate change, rising sea level combined with high tides, storms and flooding, put island communities increasingly at risk. As global sea level is rising, and it is foreseen that it will continue to rise for centuries, sustainable development on small islands is at risk because a great part of the population and vital marine resources are concentrated along low-lying coasts The Intergovernmental Panel on Climate Change (IPCC, 2013) reported that global mean sea level (GMSL) rose by 1.5 mm yr^{-1} during the period 1901–1990, accelerating to 3.6 mm yr^{-1} during the period 2005–2015. The serious changes of the marine environment are on a global scale and anthropogenic forcing has made a substantial contribution to the increase of temperature in the upper layer of the ocean covering the layer from the surface to a depth of about 700 meters. As a consequence, the upper 75 m warmed by about 0.11°C per decade over the period 1971 to 2010 (IPPC, 2014). Recent studies show the extent of the anomalies; for instance, in a region of the NW Indian Ocean with a trend of increasing temperatures, that should the trend persist in the region, temperatures could reach around 27.7 °C by 2050 (Szekielda, 2020; 2021). Related to this globally observed development of temperature increase is the extraordinary function of the marine ecosystem. For example, it was shown that the NW Indian Ocean is exposed to the fastest temperature increase in the world's ocean, and loss in chlorophyll is observed at an alarming rate

(Roxy *et al.*, 2014; Reason *et al.*, 2000; Behrenfeld *et al.*, 2006; Prakash and Ramesh, 2007; Prakash *et al.*, 2012; Roxy *et al.*, 2016; Roxy *et al.*, 2020).

With respect to future environmental changes, it can be estimated that The Bahamas may have to retreat in the future about 0.4 million people from the low elevated coastal zone. Many of its small islands are low-lying, and their environmental challenges are similar with respect to resource constraints, population dynamics and exposure to natural disasters and global change. The low topography of The Bahamas further makes it extremely vulnerable to the impact of hurricanes and as a result, people and property are at risk as well as the infrastructure that supports the tourist industry. Increasing temperature as an outcome of global warming also has a detrimental impact on the marine ecosystem, such as coral bleaching, acidification and the distribution of marine living resources. Despite the fact that The Bahamas is a grouping of islands with a tropical coastal environment, not much research on near-coastal processes in The Bahamas has been documented although environmental observations are available over the past century. In this regard, the following study will focus on the anticipated impact of global changes in The Bahamas, in particular on parameters that are vital indicators for environmental stress. The outcome of the study may assist in considering modalities to mitigate the impact of changes in the marine environment and the life-threatening development in the coastal region of The Bahamas.

MATERIALS AND METHODS

The study used remotely sensed data that were accessed from the System for Multidisciplinary Research and Applications (NASA Giovanni). The system was constructed by NASA for the analysis of Earth remote sensing data on weather, climate, atmospheric composition and dynamics, oceanography and hydrological processes (Acker *et al.*, 2006). Most data sets used in this study cover a time frame of more than ten years except for the measurement of sea surface salinity that was available only for the period September 2011 to May 2015. Therefore, data were selected for 2012 to extract information on the annual cycle of selected parameters that relate to the marine environment.

Two areas were studied that are shown in Figure 1. The first covers the wider Bahamas, part of Florida and portions of the North Atlantic Ocean. This area served to show the natural yearly fluctuation in surface temperature, salinity, precipitation and chlorophyll in order to describe the wider marine environment surrounding The Bahamas. The second data set covers the marine area of The Bahamas for the analysis of time series and long-term fluctuations with the objective to estimate anticipated trends in environmental changes within the next decades.

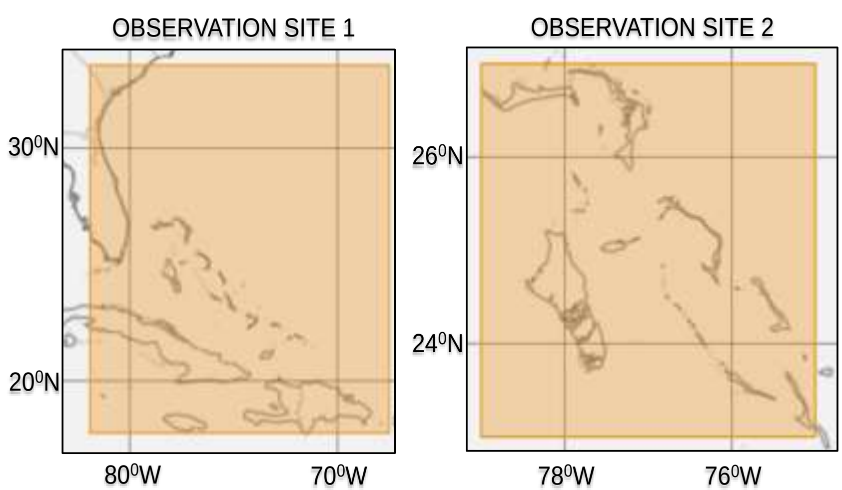


Figure 1: Location of sites referred to in the text. Site 1 analyzes data sets over the marine environment surrounding The Bahamas. Site 2 that covers the region at 79^0W, 23^0N to 75^0W and 27^0N analyzes long-term trends.

RESULTS

The marine environment

Figure 2 shows monthly averaged sea surface temperature data that indicate the major dynamics of the area. Typical for the tropical climate in The Bahamas is that sea surface temperature does not vary very much and that water temperature can be observed even above 30 °C. The yearly cycle in temperature is well pronounced and shows for the whole region its maximum in September with progression of temperature mainly in the north-south direction. The Gulf Stream to the northwest of The Bahamas is well characterized by elevated temperature and shows its flow and strong temperature gradient along the Florida coast. Water with lower temperature borders towards the North Atlantic in east and north directions.

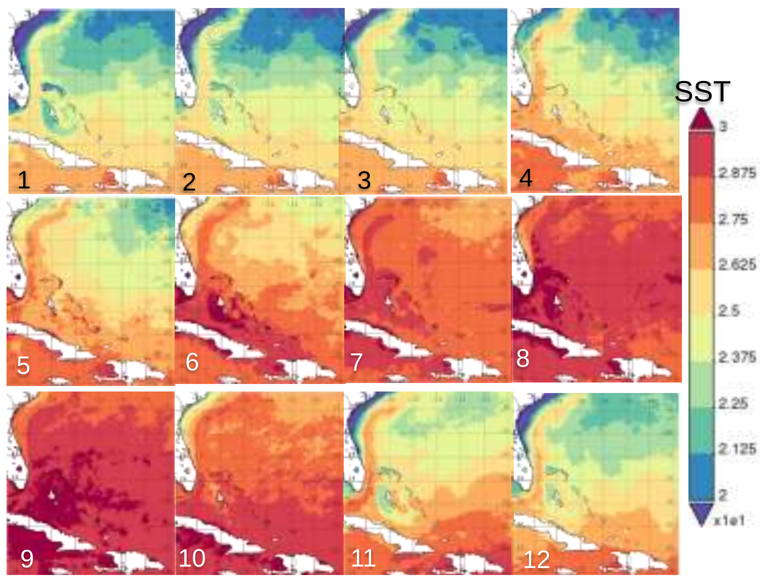


Figure 2: Monthly averaged sea surface temperature (SST in centigrade) at 4km surface resolution for 2012. Numbers in each frame correspond to the month for which data were analyzed.

The Bahamas are located in a region with low precipitation and elevated temperature, evaporation exceeds precipitation that leads to high salinity. Although the salinity data used in this study are measured at a coarse resolution of about one kilometer, they show in Figure 3 the elevated salinities during the first quarter of the year around The Bahamas Bank. Yearly fluctuations range only over a few units. In response to increase in precipitation during the summer and late Fall, salinity is reduced for the second part of the year. Salinity anomalies seem to be a common feature in The Bahamas' archipelago, and salinity anomalies can be as high as 38 psu. In the area south of New Providence Island, bank water salinity was found to reach even 42 psu, although water transported from the Atlantic to The Bahamas region a surface salinity was measured to be around 36.5 psu (Busby and Dick, 1964). The monthly averaged salinities in Figure 3 testify to the appearance of high salinities of approximately 37 psu especially during the dry season at the beginning of the year. Horizontal gradients at the surface, however, respond to variations in atmospheric conditions and intermediate changes, especially during the hurricane season (Szekielda *et al.*, 2019).

The meteorological conditions, nutrient levels and temperatures around The Bahamas do not support a high standing stock of biomass as indicated in Figure 4. Chlorophyll concentrations, as a measure of biomass, are rather low as they are typical for oligotrophic waters. However, local concentrations of chlorophyll may reach elevated values that are comparable to those found along the Florida coast.

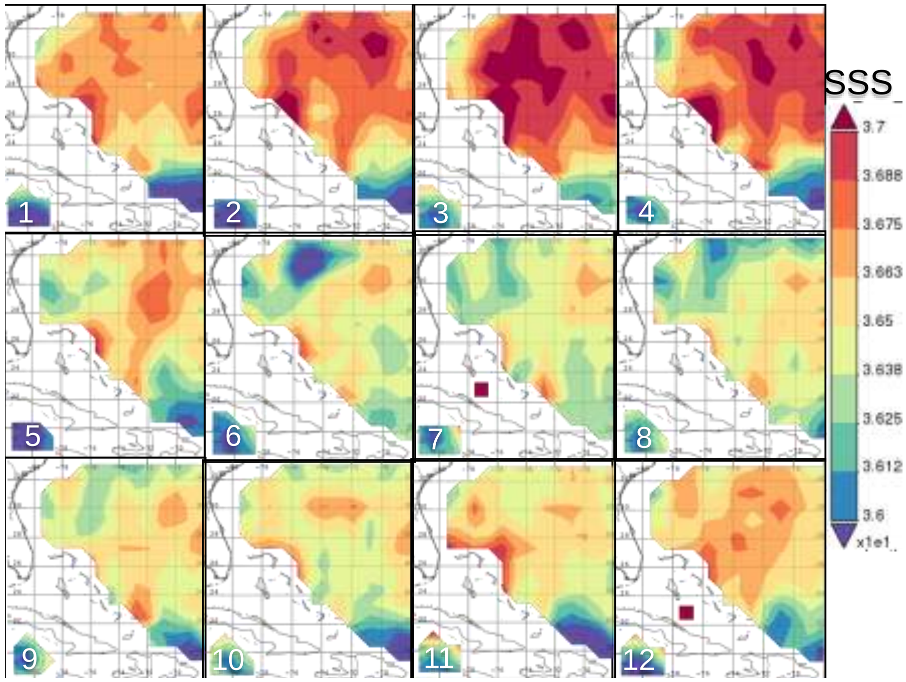


Figure 3: Rain-corrected sea-surface salinity (psu) distribution based on monthly-averaged data for 2012, at about 100 km surface resolution. Numbers in each frame correspond to the month when data were taken.

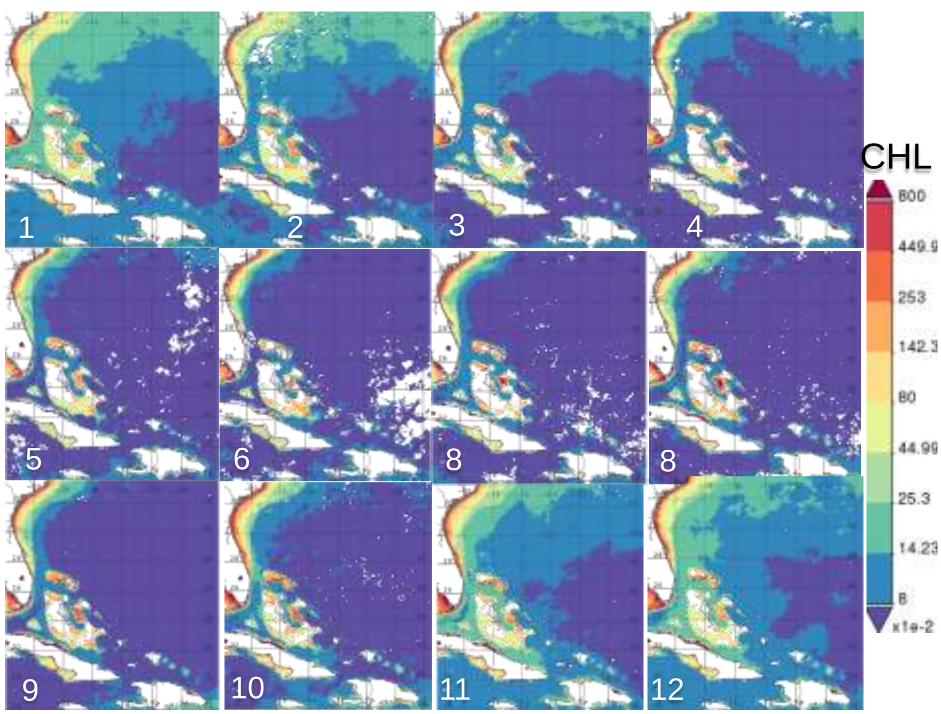


Figure 4: Chlorophyll distribution (mg m^{-3}) at four-kilometer surface resolution based on monthly averaged data for 2012 at one-degree surface resolution. Numbers in each frame correspond to the month when data were taken.

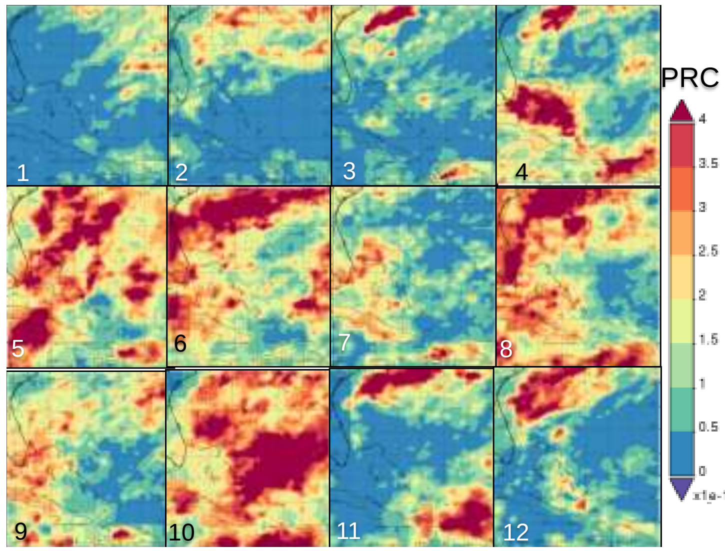


Figure 5: Monthly averaged microwave-infrared precipitation rate (mm/hr) for 2012 at 0.25-degree surface resolution. Numbers in each frame correspond to the month when data were taken.

The Bahamas show moderate rainfall with a wet season around April/May and less precipitation during the winter season, as shown in Figure 5. Highest rainfall is observed around October, occurring during the most active Atlantic hurricane season that normally extends from July to October. A significant difference in rainfall between the northern and southern part of The Bahamas is observed showing a lower precipitation range in the south.

Time series of changes in precipitation and sea surface temperature

Figure 6 shows the time series of averaged data that display the yearly cycle but also anomalous fluctuations to high levels in precipitation. The linear fit to the time series indicates an increase of precipitation although significant interannual fluctuations are observed.

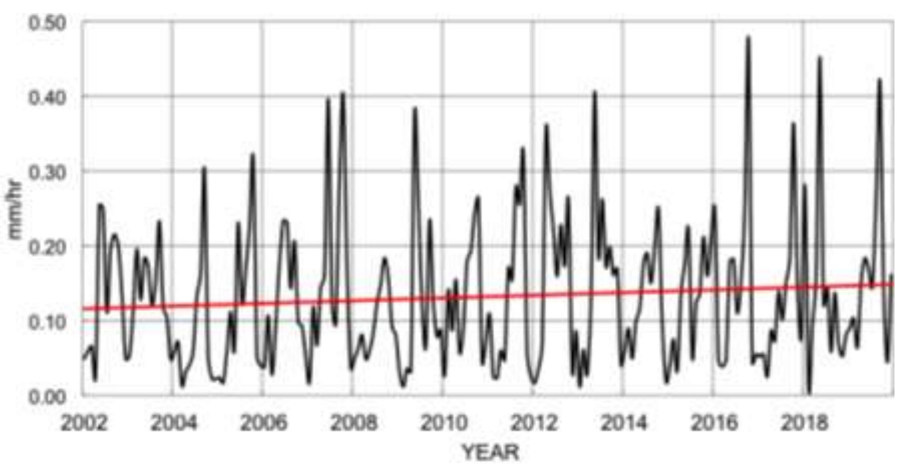


Figure 6: Time series of area-averaged monthly precipitation (mm hr^{-1}). Included is a linear fit that is shown as a red line. The location of observations is shown in Figure 1 with Site 2.

The analyzed time series of sea surface temperature is based on area and monthly averaged mean values and is shown in Figure 7. Minimum temperature was found at 23 °C but the maximum does not exceed

30C. The linear and polynomial fit were applied and are shown at an expanded scale in Figure 7B. The linear fit gives an increase of 0.7 °C while the polynomial fit reveals a temperature minimum in 2008. This minimum indicates that the global anthropogenic temperature signal is superimposed by fluctuations that may have periodicities and temperature changes through decades.

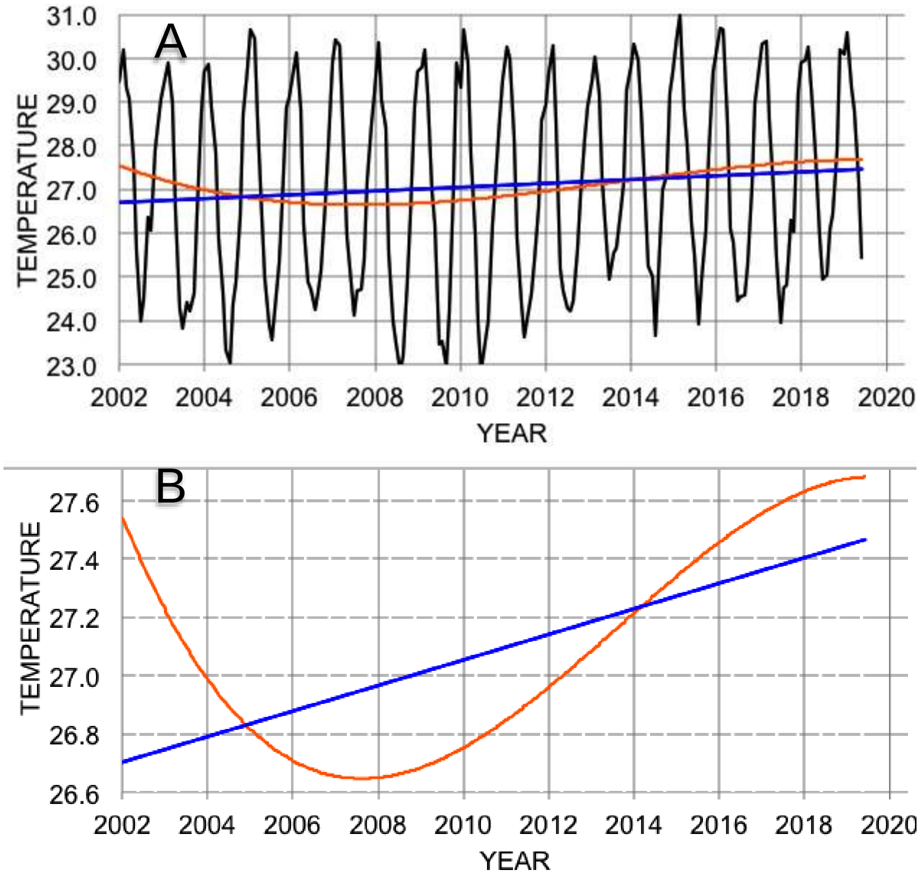


Figure 7: A. Area and monthly averaged sea surface temperature (°C), fluctuations with linear and 3rd order polynomial fit. B. Data as in A but with an expanded temperature scale for the linear (blue) and polynomial fit (red). The location of observations is shown in Figure 1 with Site 2.

Interannual fluctuation of precipitation and temperature

As small as the observed changes for precipitation and temperature are, they present an indication for larger changes of meteorological processes. However, averaging data for a whole year masks events that may act independently from each other during the seasons. Therefore, in order to separate occurring differences within a year, the data were subdivided according to seasons of which the data for precipitation and temperature changes are shown in Figure 8 and Figure 9, respectively.

The precipitation data show strong interannual variations during all seasons and lowest precipitation amplitudes are found for the period December to February while highest precipitation amplitudes are observed from September to November. The seasons show an increase over the years except for June to July that has a downward trend.

The corresponding analysis for sea surface temperature shows for all seasons a warming trend although they have a slight difference in their slope that is shown with the regressions that are included in Figure 9.

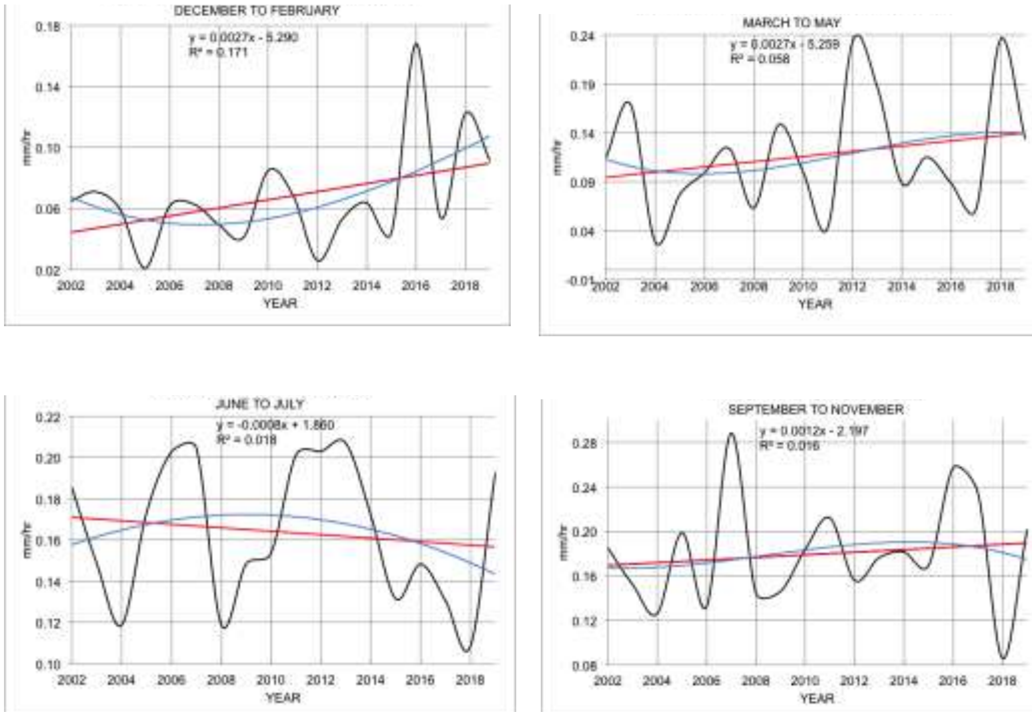
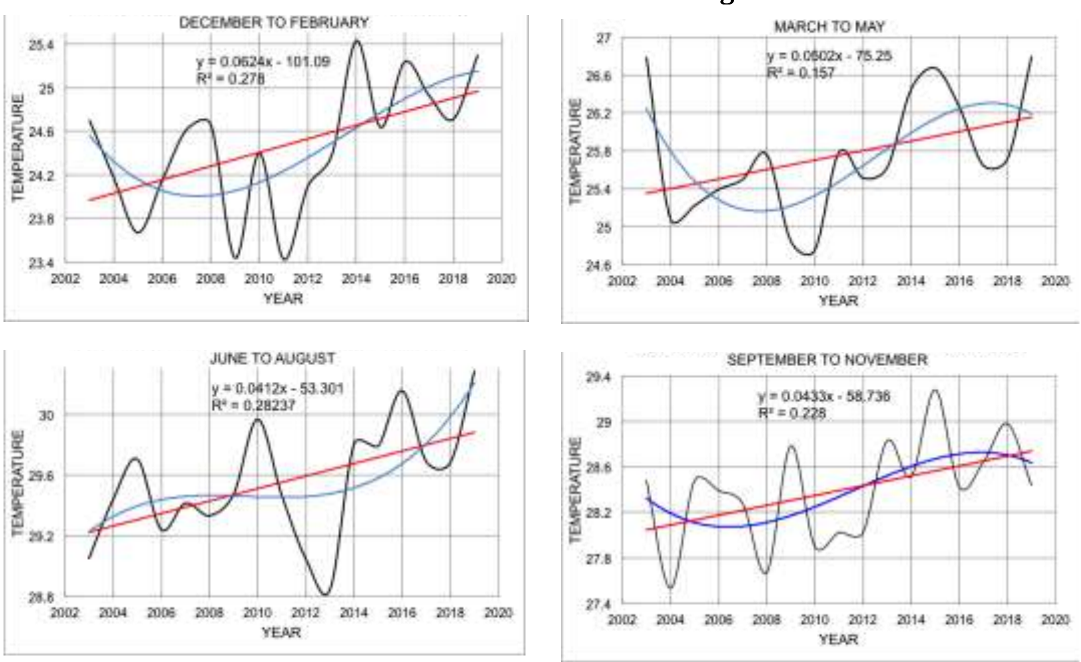


Figure 8: Bahamas interannual precipitation rate by season based on area-averaged monthly precipitation rate. Red lines show the linear regression and blue lines indicate 3rd order polynomial fit. The location of observations is shown in Figure 1 with Site



2.

Figure 9: A and monthly-averaged sea surface temperature (C) with regression analysis for seasonal trends. Red lines show the linear regression and blue lines indicate 3rd order polynomial fit. Theion of observations is shown in Figure 1 with Site 2.

DISCUSSION

Sea surface temperature is a good and robust indicator for global warming and the data set used in this study has the potential to predict temperature changes for the next decades. Table 1 summarizes and compares linear regressions for temperature that were used to estimate temperatures for several years. It is evident that over a time frame of 25 years the predicted temperature increase for all seasons is above one centigrade. The highest increase is observed for the period September to November with a maximum of 1.7C while lowest increase is 1.0C for June to August.

Table 1: Linear regression for temperature changes by seasons and estimates of temperature for selected years.

SEASONS	LINEAR REGRESSION	2010 (°C)	2020 (°C)	2035 (°C)	Δ°C 2035-2010
DEC-JAN-FEB	y = 0.0624x - 101.09	24.3	25.0	25.9	**1.6**
MAR-APR-MAY	y = 0.0502x - 75.254	25.7	26.2	26.9	**1.2**
JUN-JUL-AUG	y = 0.0412x - 53.301	29.5	29.9	30.5	**1.0**
SEP-OCT-NOV	y = 0.0433x - 58.736	27.7	28.7	29.4	**1.7**

This analysis is based on a large data set applied for the first time to show the impact of temperature change to the environment around The Bahamas, an increasing temperature trend that is related to global warming. Taking into account the findings by the IPCC that sets a threshold of 1.2 °C, it is remarkable that the marine environment of The Bahamas may soon reach a critical scenario related to the global warming trend. The data set used in this study is robust and the warming trend indicates a projection for 2035 that seems to be realistic. The analysis however remains to be refined, and further research to follow-up with a more detailed data set is planned. The predictions in this study are based on the assumption that temperature will increase in a linear fashion although the polynomial analysis indicates that the temperature increase is overlaid by longtime fluctuations.

The changes and variations in air and ocean temperatures, ocean chemistry, rainfall, wind-strength and direction, sea levels, as well as wave climate, are concerns with respect to the future of small islands (Nurse *et al.*, 2014). Related to temperature anomalies are also changes in magnitude, frequency, and temporal and spatial extent of rainfall, hurricanes and droughts. In this regard, it is of interest to note that it has been estimated that temperature rises by 2025 with a 40% chance of being 1.5 °C warmer than the pre-industrial level The Conference of the Parties on its twenty-first session, held in Paris in 2015 recommended a goal to limit global warming to well below 2 °C, preferably to 1.5 °C compared to pre-industrial levels (United Nations, 2016). If the linear projections for 2035 are valid, sea surface temperature increase in The Bahamas will surpass the lower limit of temperature increase as recommended by the IPCC.

In addition, sea surface temperature increase is not uniform and regional differences are subject to large-scale periodic interruptions. Similar development is observed in sea-level rise although the Caribbean region shows over the last 60 years a mean rate of rise that is similar to the global average of approximately 1.8mm yr^{-1}.

Global climate change challenges the socio-economic development because mitigation and adaption to the impact of climate change has high financial implications. For instance, risk assessment have shown likely losses in terms of real estate value as well as potential income, due to storm surges in connection with sea-level rise (Sealy *et al.*, 2014, Sealy and Strobl, 2017). Losses will have far-reaching social-economic consequences for The Bahamas because flooding and erosion due to global change impact tourism with significant losses in revenue (Pathak *et al.*, 2021). The Bahamas National Report (2012) addresses those concerns with respect to global climate change, and included in the integrated management plan, adaptation strategies that focus on indirect economic benefits such as overcoming disincentives to sea level rise. However long-term planning on issues related to climate change and sea

level rise depends on reliable data information that is missing in many small islands of which The Bahamas is not an exception.
Immediate action is especially important in The Bahamas with regard to environmental, health and economic impacts that have resulted from global warming. Furthermore, sea surface temperature increase in The Bahamas needs to be viewed as well against the outcome of the IPCC studies on small islands, particularly on climate change and the vulnerability of small islands.

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