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Research Article

SEASONAL AND NIGHTTIME TEMPERATURE CHANGES AROUND SMALL ISLANDS: THE BAHAMAS

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ABSTRACT
Sea surface temperature trends in The Bahamas were analyzed from 2003 to 2023. Although the data set is limited to two decades, it extracted inter-annual changes that are overlaid by a multi-decadal signal that may mask local trends and internal variability of sea surface temperature. The estimated increase of temperature for the period 2002 to 2023 is approximately 0.68^0C that corresponds to approximately 0.03^0C y^{-1}. Although data for the period 2002 to 2013 showed a temperature increase of around 0.03^0C y^{-1}, an increase of 0.08^0C y^{-1}, however, is observed for the period 2013 to 2023 that indicates an unusual accelerated local warming. The temperature distribution pattern for both periods is almost identical although they were exposed to a different rate of temperature increase. Thermal images of daytime temperature and the difference image of day and nighttime temperatures show the wide range of patterns that are generated due to different oceanic conditions and varying bathymetry. The day-night-difference images show that the east coast of Abaco and the east coast of Andros have less cooling at night during the period 2013 to 2023, compared to the previous decade. The connection between the North Atlantic and The Tongue of The Ocean shows slight warming although the North Atlantic surface water in the vicinity of The Bahamas does not reveal any substantial warming. Contrary to the warming in most regions of The Bahamas, part of the Tongue Of The Ocean region is exposed to slight cooling at night during 2013 to 2023. The average temperature day-minus-night shows increasing patchiness with increasing temporal resolution. Estimates for trends in seasonal temperatures showed the lowest rate of increase for the summer season with an estimate of about 0.016^0C y^{-1} followed by the September to November season with a rate of about 0.062^0C y^{-1}. The highest abnormal rate of increase is found for the two seasons March to May and December to February with about 0.079^0C y^{-1} and 0.073^0C y^{-1}, respectively.

Keywords: *Bahamas, Sea Temperature Increase, Day-Night Difference, Projection*

INTRODUCTION
Global warming is the most alarming development in the marine environment that is responsible for declining polar sea ice and increasing sea level. Despite international efforts to reduce carbon dioxide emission in order to control global warming CO_2 concentrations in the atmosphere, CO_2 concentration reached the highest levels in 2023 and will continue to rise. This is amid the attempt in Paris 2015 (United Nations, 2016), to limit the rise in global warming to below 1.5 ^{0}C. However, the global temperature level has already passed this benchmark, and the global temperature is at 1.56 ^{0}C above pre-industrial temperatures. The impact of global warming is best demonstrated with Greenland and Antarctica that lost ice at an accelerated rate compared to the ice coverage thirty years ago. Feedback mechanisms between processes in the atmosphere and the oceans are not fully understood, but changes in ocean currents and interruption of the marine ecosystem are anticipated with the danger that a tipping point may be already reached by passing a critical increase in global temperature change. An example of the impact of local warming is demonstrated with the appearance of hyperpycnal water at around 31^0C that can be formed at the Great Bahama Bank due to a combination of local warming, reduced evaporation, and consequent bleaching events (Smith, 2021; Oehlert *et al.*, 2023). In addition, unusual temperature changes resulted in the

increasing frequency of whitings in The Bahamas after 2011 by a factor of three compared to records between 2003 and 2010. Although there is some uncertainty in forecasting and assessing the impact of global warming, there is evidence that the level of expected impact has even been underestimated. For instance heat content of the global ocean reached a maximum in 2022, and compared to previous years, almost doubled (Storto and Yang, 2024). It has been shown that the impact of climate change is triggering or enhancing environmental events in the coastal and marine environments of Caribbean small islands (Stephenson and Jones, 2017; Szekielda, 2022). These issues are in particular a threat to island societies with high population density that occupy limited coastal space. Furthermore, many small island developing states are not in the position to challenge the social and economic consequences of global warming, because mitigation and adaption to the impact of climate change has high financial implications. However, many tools are now available to develop environmental assessments in order to provide inputs for possible action on national planning that can be used for policy formulation. Sea surface temperature warming is a global development but it also shows the impact on a local level in the Caribbean Sea and surrounding regions. For instance, the early rainfall season and the late rainfall season in the Caribbean show different temperature trends at 0.016 ^{0}C y^{-1} and 0.021 ^{0}C y^{-1} respectively, and extreme fluctuations in temperature time series showed possible correlation with El Niño and the Southern Oscillation (Glenn *et al.*, 2015).

As The Bahamas is a tourism-based economy, it also has to address climate change and its impacts on tourism and has to evaluate climate adaptation in current plans and policies (Pathak, 2020; Pathak *et al.*, 2021). It is evident that, like in other islands, the marine environment of The Bahamas is already exposed to a critical scenario that is related to the global warming trend. A risk assessment on possible losses of coastal properties in The Bahamas due to increasing tropical storm surges and sea-level rise demonstrate the serious upcoming challenges for small islands (Sealy and Strobl, 2017). In a survey on the impact of climate change in The Bahamas, it was shown that the public has limited awareness of climate change and knowledge of specific impacts of climate change on the environment (Thomas and Benjamin, 2018).

There is evidence that the increase of temperature during the last years accelerated, but the changes are not uniform, and many regions however show specific anomalies in temperature changes. In particular, decadal fluctuations in climate introduce anomalies that are superimposed over local changes in climate and may mask the real local climate change signals. Furthermore, interannual sea surface temperature measurements in The Bahamas show that each season has a specific warming trend (Szekielda and Watson, 2021). A rough prediction in The Bahamas for 2035, shows that the highest temperature increase may be for September to November with 1.7 °C, while lowest predicted increase is about 1.0 °C for the season June to August. This indicates that The Bahamas may be already exposed to a critical scenario under the assumption that linear projections are valid. Such observations of sea surface temperature have a parallel to air temperature trends that show that the frequency of warm days, warm nights and extreme high temperatures has increased (Stephenson *et al.*, 2014). This also demonstrates that the daily cycle, building of wakes in the vicinity of islands, seasonal changes and longtime-time fluctuations have to be fully comprehended when forecasting the possible impact of climate changes around small islands. It has to be stressed that small islands have a very peculiar environment with respect to the influence of bathymetry and meteorological conditions on the sea surface temperature, and that local temperature changes are probably more important to local management than data on global changes. In connection with previous studies in The Bahamas, it is therefore of interest to identify possible changes in trends that may have occurred during the last years. Thus, the following study will highlight with sea surface temperature measurement the level of changes around the islands of The Bahamas.

MATERIALS AND METHODS

METHODS AND SHORT DESCRIPTION OF THE TEST SITE

The study uses satellite remotely sensed temperatures that were processed with Giovanni, a system for multidisciplinary research and applications that was accessed via https://giovanni.gsfc.nasa.gov/ (Acker and Leptoukh 2007). The area of investigations is shown in Figure 1 and covers the larger part of The Bahamas but it is referred to in the text as The Bahamas. Time series of sea surface temperature covered the years 2002 to 2023. The data are based on 11μm-measurements and are monthly averaged at 4 km resolution. This set was also sub-divided into observations from January 2003 to December 2013 and into the second set that covered January 2013 to December 2023.

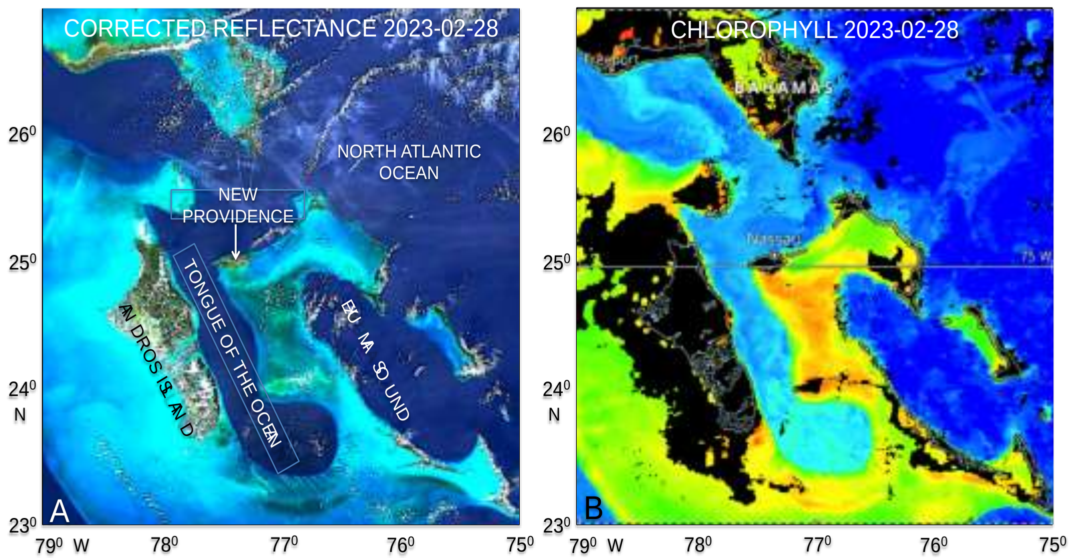

Figure 1: The test site includes the major part of The Bahamas covering the area 23⁰N, 79⁰W to 27⁰N, 75⁰W where Figure 1A highlights the major bathymetric features and Figure 1B, chlorophyll concentrations (mg m^{-3}).

Figure 1A shows the major bathymetric features and Figure 1B shows the chlorophyll concentrations that highlight the Great Bahama Bank with slightly elevated concentrations. The Tongue of the Ocean shows a modest increase of chlorophyll concentrations surrounding the southern part, and low concentrations are found in the Exuma Sound and North Atlantic Ocean water. However the high reflective bottom especially in the Great Bahama Bank influences the chlorophyll concentration-algorithm.

RESULTS, DISCUSSIONS AND CONCLUSIONS

Temperature series for the investigated region is shown in Figure 2 for the period June 2002 to June 2023, and included, is the corresponding two period moving average in Figure 2B for data shown in Figure 2A. The temperature series in Figure 2A shows fluctuations in surface temperature especially in 2004 and in 2008 to 2011 with minimum temperature around 23^0 C. While the minimum temperatures during the winter seasons show substantial fluctuations, the maximum summer temperature is more uniform. Figure 2B shows that a significant increase of sea surface temperature occurred in 2013 that reached in the averaged data 27.6^0C in 2015. From Figures 2A and 2B, it can be deducted that inter-annual changes are overlaid by a multi-decadal signal that may disguise local trends and internal variability of sea surface temperature. The polynomial fit of the data in Figure 2C also indicates that the temperature change undergoes long-term periodical oscillations, and most probably those changes are related to temperature variability in the North Atlantic temperature due to the El Niño Southern Oscillation.

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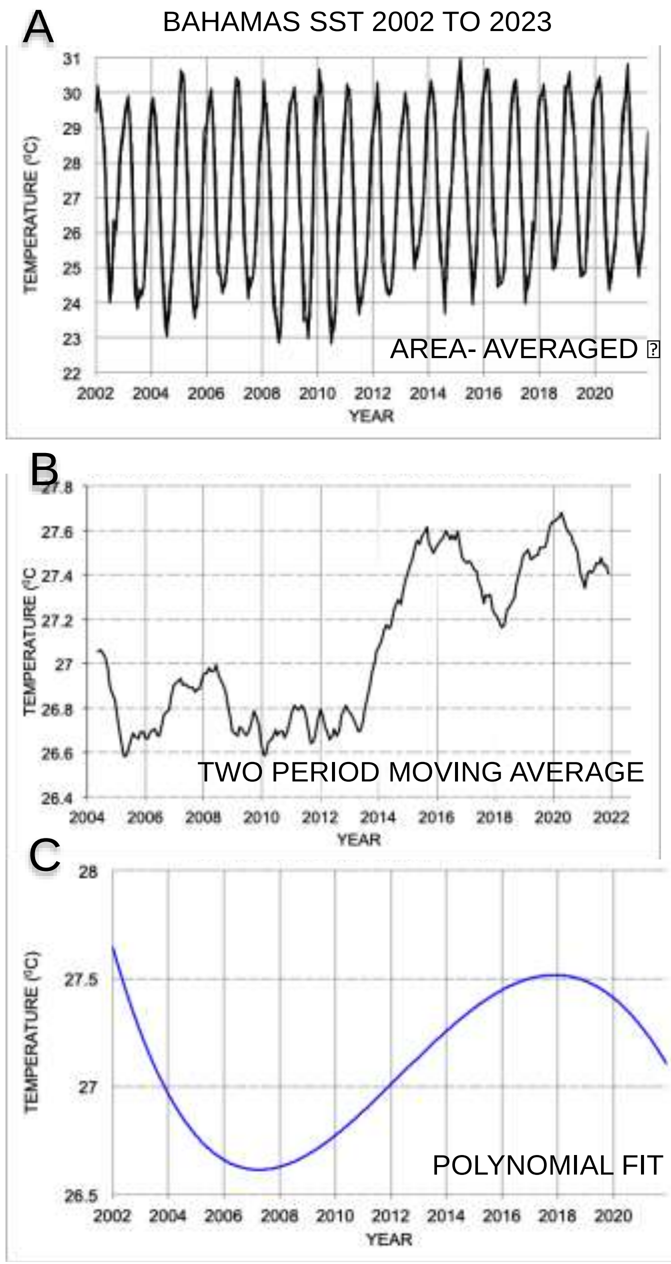

Figure 2 A: Area averaged sea surface temperature for June 2002 to June 2023. Figure 2B: Two period moving average for data shown in Figure 2A. Figure C: Polynomial fit.

The linear regression for the time frame 2002 to 2023 showed an increase of approximately 0.68^{0}C that would correspond to a rate of approximately 0.03^{0}C y^{-1}. Parallel to sea surface temperature, the atmosphere trend shows that the Caribbean region warms by about 0.019^{0}C y^{-1}, but the mean of daily minimum temperature may have a more pronounced warming of about 0.028 ^{0}C y^{-1} (Stephenson *et al.*, 2014). There is evidence that the slope of sea surface temperature changed during the last years, and therefore it is challenging to compare the trends in The Bahamas with two data sets that cover the periods 2002 to 2013 and 2013 to 2023.

The general trend of the temperature analysis for 2002 to 2023 shows an average increase over 21 years of about 0.03 ^{0}C y^{-1}. However, the subdivision of data shown in Figure 3A and 3B, gives for the period 2002 to 2013 a temperature increase of around 0.03 ^{0}C y^{-1}, but an increase of 0.08 ^{0}C y^{-1} is observed for the period 2013 to 2023. Although the data set used for this analysis covers a very short time frame, it still provides an approximation of possible acceleration of local warming and possible short-time fluctuations of the temperature trend in The Bahamas.
The complexity in temperature distribution and changes at local level compared to global changes demonstrate the limitation of any meaningful predictions for appropriate planning and management that is based on global forecasting. In an attempt to estimate possible changes that can be expected on the local level, the temperature data for 2004 to 2022 were subdivided into seasons with the objective to apply linear equations to estimate the rate of temperature change for each season for The Bahamas, and estimate a possible temperature increase by 2040.

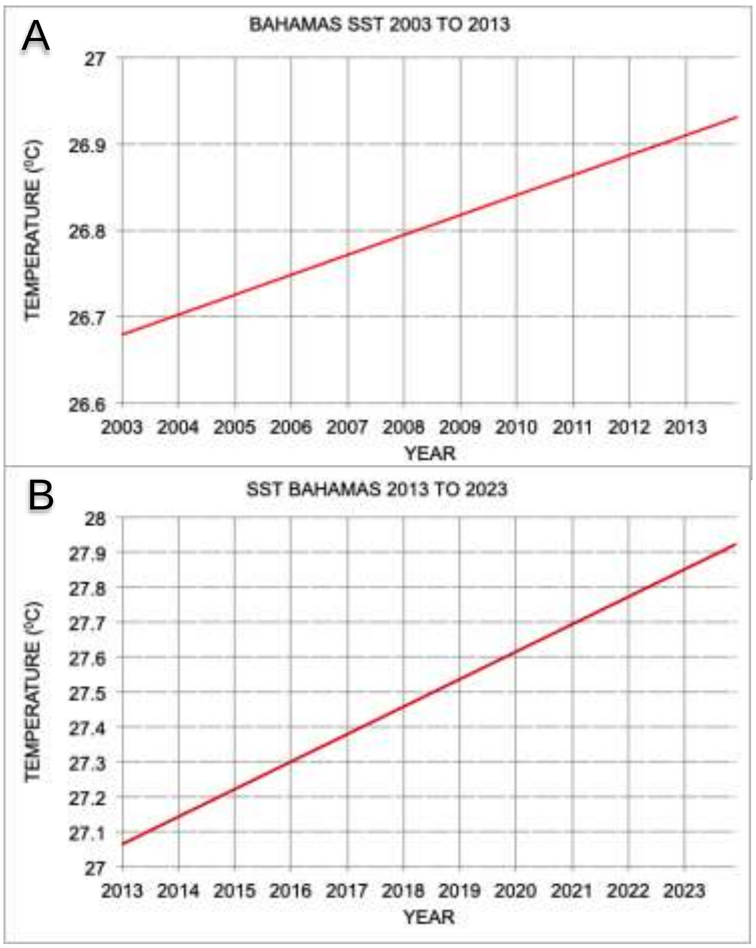

Figure 3: Linear regressions of area-averaged sea surface temperature. 3A: January 2003 to December 2013. Figure 3B: January 2013 to December 2023.

The results in in Table 1 and Figure 4 show that each season has different characteristics and slopes. The lowest estimate for temperature increase is for the summer season, with an estimate of about 0.016 ^{0}C y^{-1} followed by the September to November season with a rate of about 0.062 ^{0}C y^{-1}. The highest rate of increase is found for the seasons March to May and December to February with about 0.079^{0}C y^{-1} and 0.073^{0}C y^{-1}, respectively.

Table 1: Seasonal changes based on linear regressions from results shown in Figure 8 with estimated forecasting to 2040.

SEASON	EQUATION	2020^{0}C	2040^{0}C	Δ^0C	^{0}C y^{-1}
DJF	0.0733x - 122.9	25.17	26.63	1.46	0.073
MAM	0.0784x - 131.97	26.40	27.97	1.57	0.079
JJA	0.0163x - 3.2572	29.67	29.99	0.32	0.016
SON	0.0621x - 96.586	28.86	30.10	1.24	0.062
AVERAGE		27.53	28.67	1.15	0.058

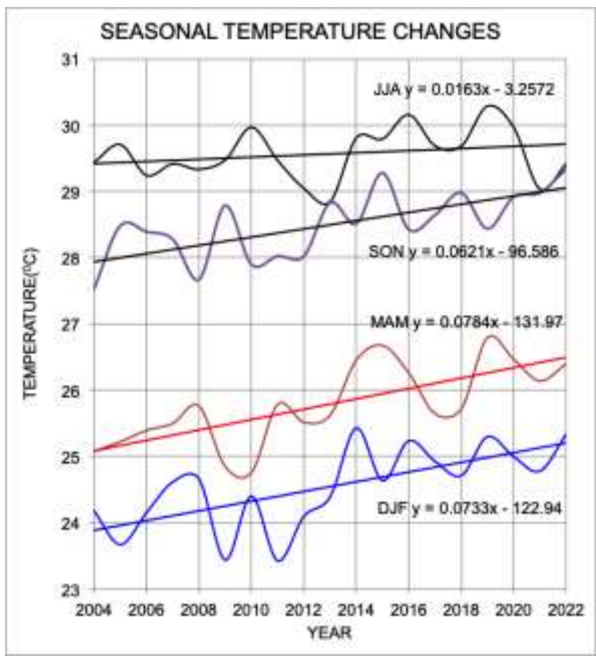

Figure 4: Temperature changes by seasons with the corresponding linear regressions and equations.

The substantial difference in temperature change is apparent throughout the studied region as indicated in the comparison in Figure 5. By comparing Figure 5A and 5B, it becomes evident that the whole Bahama region was exposed to the same increase in temperature. The comparison of 5A and 5C shows that the distribution patterns in temperature is almost identical although the northern part of The Bahamas deviates from this trend with a slight increase in temperature compared to the southern part.

The difference in heat capacity between land and water is responsible for developing different diurnal temperature cycles and as a consequence, the temperature fluctuations of land and water vary at different rates. Furthermore, currents, the depth of the water column close to the islands, and the building of surface wakes (Szekielda, 2023), influence the rate of temperature change and the distribution patterns around The Bahamas. This can be demonstrated with the daytime sea surface temperature in Figure 6A and the difference of day-minus-night averaged temperature in Figure 6B, that shows the effect of land surfaces and bathymetry on temperature distribution.

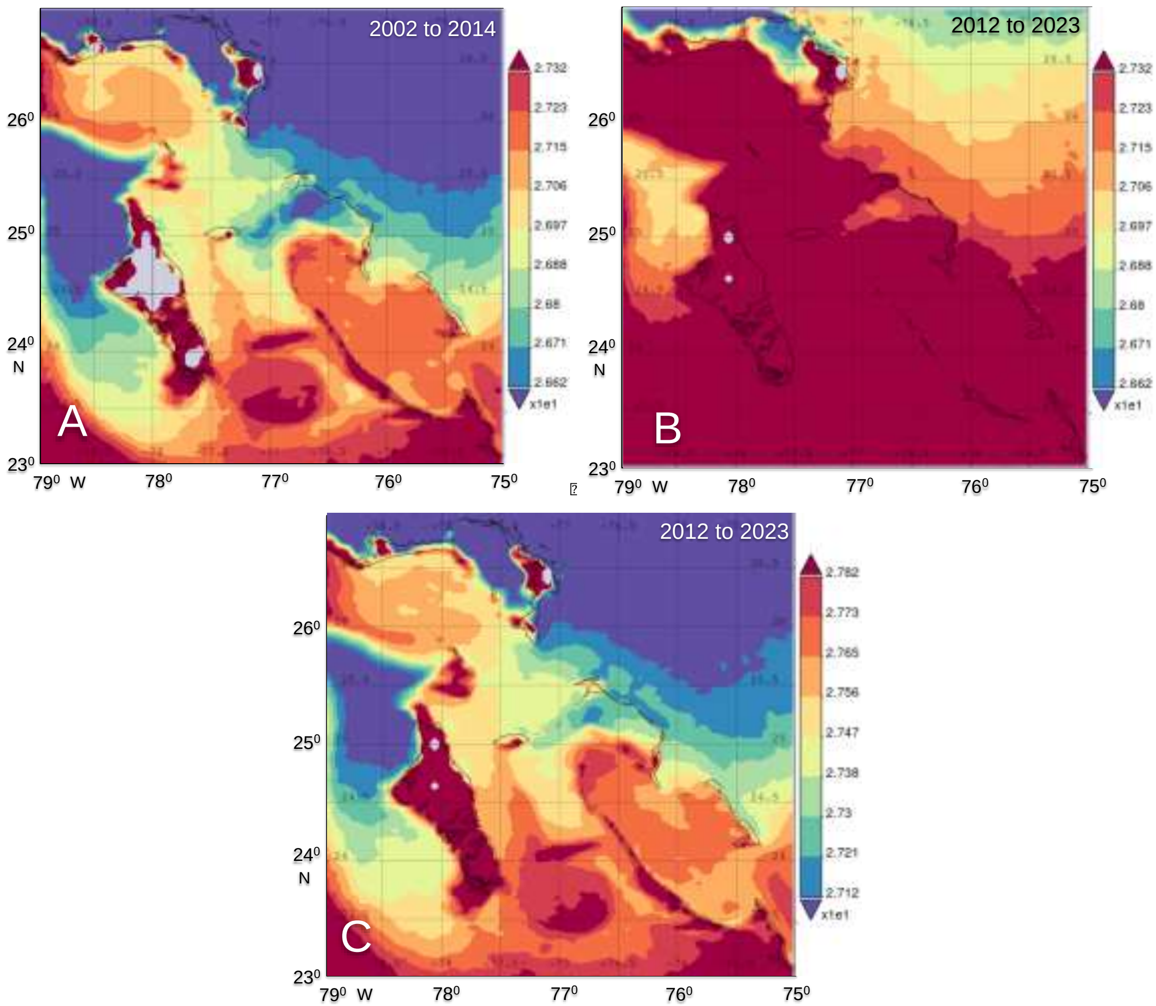

Figure 5: Time-averaged daytime sea surface temperature. 5A: 2002 to 2014; 5B 2012 to 2023. Both data sets are displayed with the same dynamic range of color annotations. Figure 5C shows the temperature display of Figure 5B with an adjusted dynamic range of 0.5^{0}C.

The anomalous surface temperature in the south of the Tongue Of The Ocean is explained by the numerous islands, reefs and shoals that surround the southern part and prevent extensive water exchange with the cooler North Atlantic Ocean water. Andros Island also shows a thermal anomaly that is based on the geomorphological properties of the island because the island is partly covered with surface water. These properties also effect the diurnal temperature change that is shown in Figure 6.

Figures 6A and 6B indicate that many small islets, cays and tidal swamplands determine the day-minus-night temperature difference of the near-shore water as well. The impact of bathymetry on the diurnal cycle is shown in the north with the Little Bahama Bank and Great Abaco that results in the night cooling of around 4.4^{0}C. Similarly, the neighborhoods of the islands of Eleuthera and Exuma show strong night cooling. Low diurnal temperature changes are observed at the southern part of the Tongue of the Ocean close to the deep slope in bathymetry.

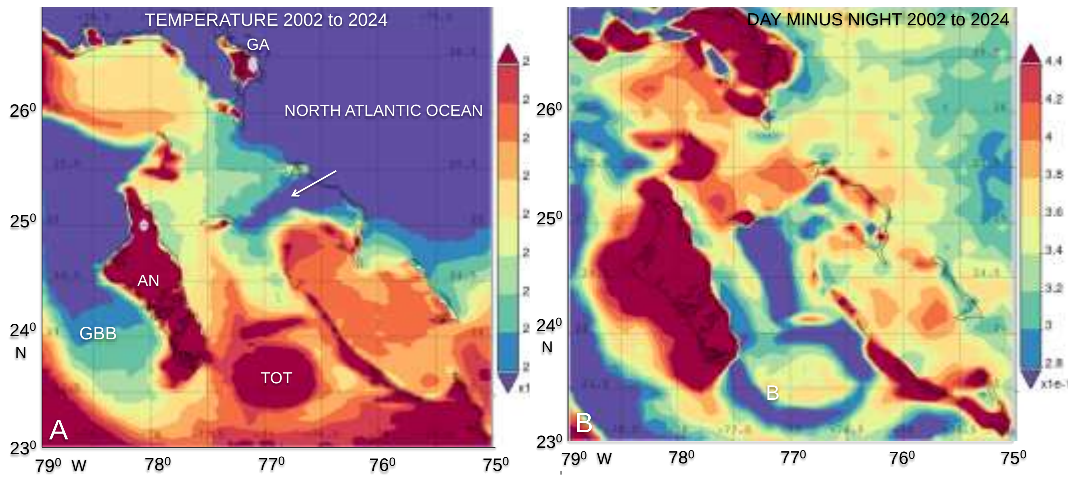

Figure 6: A: Averaged surface temperature for 2002 to 2024; TOT: Southern part of the Tongue of the Ocean, AN: Andros, GBB: Great Bahama Bank, GA: Great Abaco. The Tongue of the Oceans has only in the northern part an exchange with the open ocean through the New Providence channels that is indicated by the arrow. Figure 6B: Temperature difference for day-minus-night data.

The image of daytime temperature and the difference image of day and nighttime temperatures show the wide range of patterns that are generated due to different oceanic conditions and varying bathymetry. That makes it challenging to identify possible changes in the diurnal temperature cycle that may occur on a time scale similar to the global change signal, and whether the temperature in the diurnal cycle is equally distributed throughout The Bahamas. This issue was addressed with a comparison of day-night-time differences for 2002 to 2013 and 2012 to 2023 and the results are shown in Figure 7A and 7B respectively.

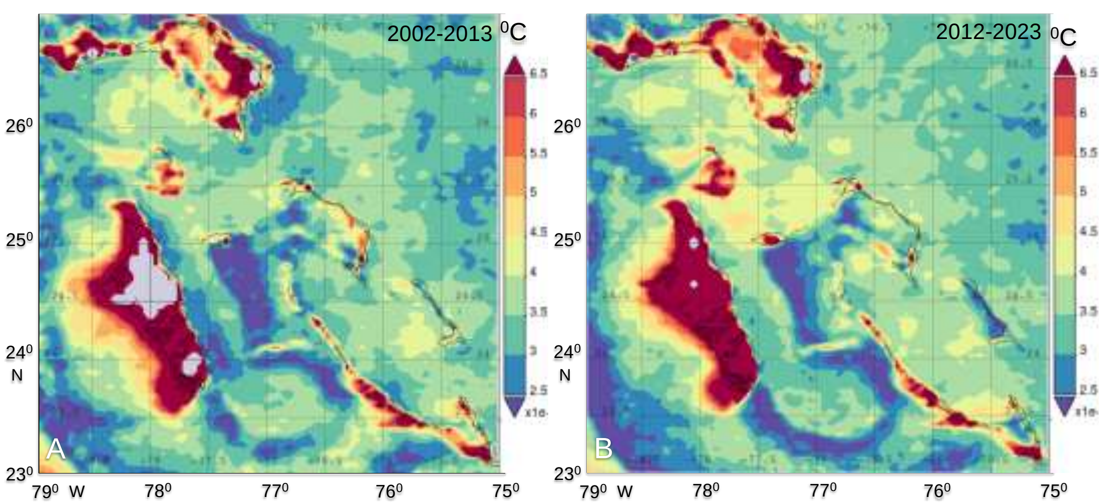

Figure 7: Difference of time-averaged temperature day-minus-night- measurements. Figure 7A shows the average temperature image for 2002 to 2013 and Figure 7B shows the average temperature image for 2012 to 2023.

The day-night-difference images show smaller changes in the pattern of temperature distribution: In the north, the east coast of Abaco underwent warming and along the east coast of Andros, increasing temperature is also observed. The connection between the North Atlantic and The Tongue of The Ocean shows slight warming although the North Atlantic surface water in the vicinity of The Bahamas does not reveal any substantial warming. Contrary to the warming in most regions in The Bahamas, part of the Tongue Of The Ocean region is exposed to slight cooling. This analysis leads to the notion that the rate of night cooling is area specific whereas the daytime sea surface temperature shows less variation.

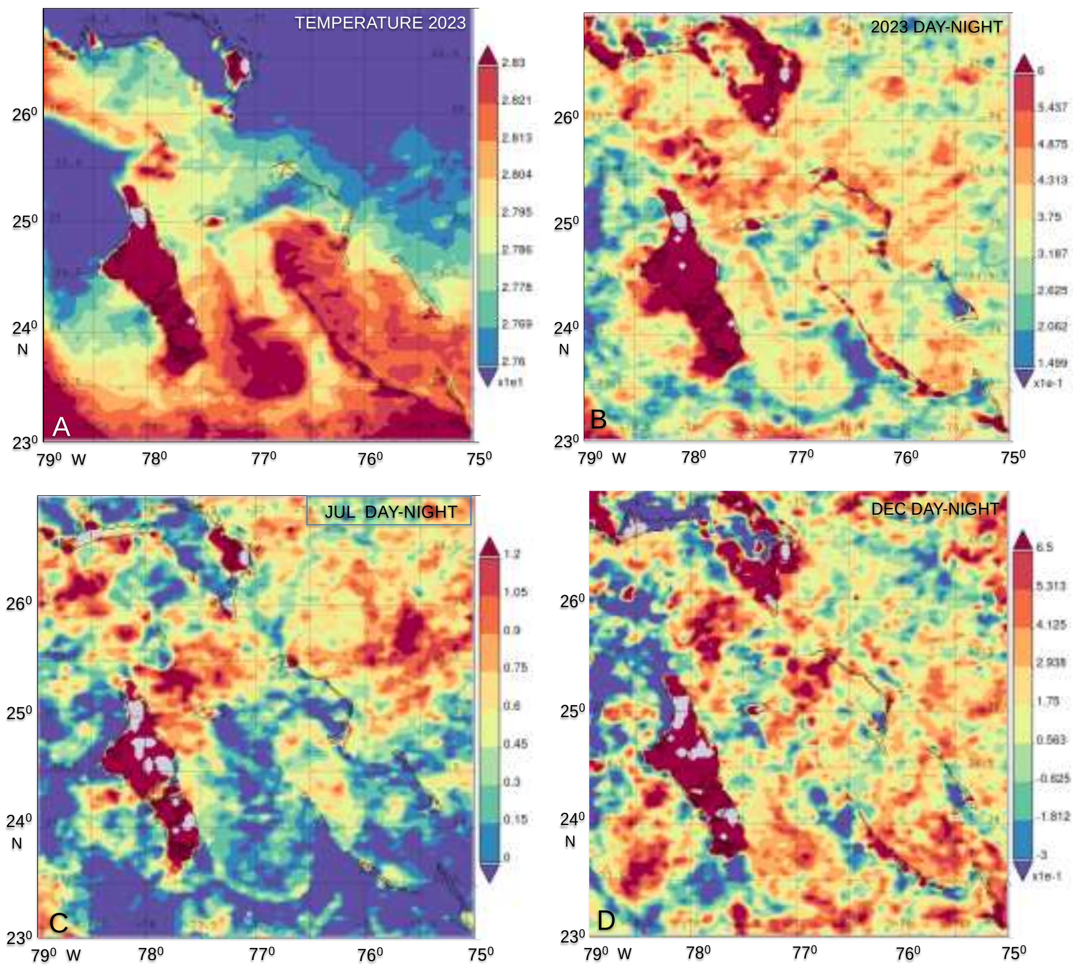

Figure 8: A: Average temperature for 2023; 8B: Difference day minus night temperature for 2023; 8C: Difference day minus night temperature for July 2023; 8D: Difference day minus night temperature for December 2023.

The average temperature over a decade results in a smooth image display for the daytime temperature and the difference data, but at higher temporal resolution, the distribution pattern becomes chaotic as is demonstrated in Figure 8 with an analysis of temperature distribution in 2023 for various time intervals. The average temperature for 2023 in Figure 8A shows that the temperature patchiness is comparable to the patchiness shown in Figures 5A and 5C, but the difference image for 2023 in Figure 8B shows random distribution patterns that become more intense when the temporal resolution is increased to monthly averaged data for July and for December. The difference image for July shows a north south gradient with lowest temperature changes in the south, whereas the corresponding temperature display for December is more chaotic, and the western region shows a slightly lower cooling at night than the west.

The trends in sea surface temperature that are derived in this analysis seem to be extremely high, but air temperature measured during the last decade also indicates accelerated warming. The World Bank (2021) reported that the mean air temperature in The Bahamas has increased since 1960 at an average rate of 0.011^0C y^{-1}, and the recent rate increased to about of 0.026^0C y^{-1}, with seasonal variations that show the fastest rates in June to August and September to November at rates of 0.013 and 0.015^0C y^{-1}, respectively. Temperature changes vary amongst the different islands, and faster warming is observed in the northeastern region compared to the southwestern islands.

The surface air temperatures were unusually high in 2023 with temperatures increase of about 0.3°C compared to 2022, and it seems to be a combined effect of long-term global warming and a strong El Niño (Cheng *et al.*, 2024). Consequently, the strong oscillations in the atmosphere and in the ocean introduce an uncertainty in forecasting and especially when linear regressions are used. Therefore, the results in this study provide at best a general indication of possible changes in the marine environment around The Bahamas, but it may also be valid for other small island groups worldwide and specifically for those in the Caribbean region. It is therefore worthwhile to review the characteristics of all islands and design appropriate monitoring strategies to fully understand the complexity of their surrounding environment.

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