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Detection and spatio-temporal variation of marine heatwaves in the Gulf of Guinea, Nigeria

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Time series analyses spanning 30 years (1988 - 2017) on spatial and temporal variations in sea surface temperatures reveal the occurrence of marine heatwaves (MHWs) within the Nigerian segment of the Gulf of Guinea. For specific focus, three locations were also chosen along Nigeria's coastal zone, namely Lagos lagoon (western region), the Niger Delta (Forcados/Central region) and outer Cross River estuary (eastern region). Daily SST data was subjected to MHW detection algorithm, and then examined using Gaussian and Poisson distribution models to delineate the distribution of maximum intensities and frequency of occurrence of these extreme events, respectively. Determining the likelihood difference of maximum intensities of MHWs and the association between MHW count and occurrence year during the period was done using Kruskal-Wallis and Kendall rank correlation tests, respectively. Results show that the entire study area has been experiencing MHWs more frequently in recent decades, with the northwest region having higher counts. Strong seasonality exists, as more MHWs occurred in winter months (October to May). Peak month for MHW occurrence over the entire study area was May. November is shared as a peak month for the three focus coastal locations, although MHWs in Cross River and Niger Delta locations exhibited multi-modal patterns. None of the MHWs in Lagos location was categorized as severe. This study contributes to the World Climate Research Programme Grand Challenge on Weather and Climate Extremes.

Key words: Marine heatwaves, extreme events, Gulf of Guinea, climate change, remotely-sensed SST.

INTRODUCTION

Marine heatwaves (MHWs) are extreme thermal events that occur in the ocean and can have impact on ocean ecology and the human populations that rely on them. MHWs could be described as prolonged, discrete anomalously events characterized by intensity, rate of evolution, duration and geographical spread (Pearce and Feng, 2013; Caputi et al., 2016; Hobday et al., 2016;

Byrne et al., 2018). MHWs occur in the ocean when observed sea surface temperatures, for a minimum period of 5 successive days, exceed a threshold, which is usually the 90th percentile relative to the local climatological mean for 30 years or more (Hobday et al., 2016). Since the sea surface is a medium for important teleconnection and exchanges between the ocean and

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atmosphere, MHWs are caused and driven by a combination of oceanographic and atmospheric processes such as net heat flux by ocean currents, thermodynamic effects of prevailing surface winds, warming from atmospheric heatwaves or overlying warm air, the warm phase of the El Niño Southern Oscillation, and the Pacific Decadal Oscillation (Hobday et al., 2016; Scannell et al., 2016). The occurrence of MHWs have ecological implications, and so, MHWs are increasingly grouped among extreme events in the ocean that could cause sustained catastrophic effects on marine ecosystems, including the depletion of marine flora and fauna, as well as coastal fisheries or shrimp stock. Thus, human populations that depend on the marine environment for food, wellbeing and livelihood are also negatively affected. Recent observations confirm that fishery resources and most marine ecosystems are highly vulnerable to the militating effects of MHWs (Cupti et al., 2016; Walsh et al., 2018).

A comprehensive study by Oliver et al. (2017) showed that the 2015/2016 Tasman Sea marine heatwave was associated with the appearance of unusual species, death of wild molluscs, and outbreaks of diseases in farmed shellfish around coastal near-shore environment. The physical driver of this extreme event was the anomalous converging of heat linked to the southward flowing East Australian current. The recent increase in frequency and severity of regional or local scale extreme events such as atmospheric heat waves, deoxygenation events, storms, gales, and floods especially in tropical regions, can be ascribed to climate change (Trenberth et al., 2007). Walsh et al. (2018) reported the occurrence of the Alaska marine heat wave in 2016 as extraordinary, exacerbated by abnormal sea surface temperatures and prevalent warm water attributed the event to human-induced climate change factors. Climate-controlled phenomenon influencing the temperate reef communities in Australia were reported to be responsible for the disappearance of kelp forests with replacement by seaweeds, corals, invertebrates and fishes characteristic of subtropical and tropical waters (Wernberg et al., 2016). Climate change is a threat-multiplier in the frequency of occurrence and intensity of MHWs.

For a period of 49 years (1950 - 1998), Odekunle and Eludoyin (2008) examined and mapped the mean sea surface temperature (SST) patterns over the Gulf of Guinea (GoG); the temporal variability as well as changes and anomalies in these patterns were reported. Although their study was done to improve understanding of the relationship between SST fields and precipitation in West Africa, some of the observed anomalies might have been associated with MHWs in the distant past. Sea surface temperatures that exceed long-term average values do not necessarily represent a MHW according to the statistically rigorous definition of Hobday et al. (2018). This present study analysed SST over a recent climatic period of 30 years (1988 - 2017) in the GoG and Nigerian

coastal subdivisions, with the aim of detecting MHWs and investigating variations in their climatological characteristics (maximum intensity and frequency). Therefore, the main objectives of this study include (1) detecting and categorizing MHWs in order of severity, (2) investigating the variation of monthly occurrence of marine heatwaves, (3) examining the inter-annual MHW maximum intensity distribution and comparison of MHW categories, (4) determining and mapping the long-term trend of the inter-annual occurrence of MHWs, comparing MHW intensities, and evaluating the association between MHW count and year of respective occurrence. In this research work, the extreme events are defined and categorized in order of severity from gridded SST measurements. Then, mapping and statistical approach was employed to understand the spatial trend of MHW occurrences in the entire region. The monthly distribution and comparison of maximum intensities exhibited across the three Nigerian coastal sites, as well as test for monotonic trend of MHW counts were also investigated. Elsewhere, emerging research has been important for understanding, observing and forecasting MHWs. However, in the GoG no physical study has been done in this regard until now. This present study paves the way for further work on identification of dominant physical drivers, prediction of MHWs in the GoG, and most importantly, ecological and socioeconomic impacts.

MATERIALS AND METHODS

Description of study area

The study area is a segment of the Gulf of Guinea (GoG) in the southern Atlantic ocean that borders the southernmost part of Nigeria (latitudes 3° 52' 30"N to 6° 22' 30"N and longitudes 2° 37' 30"E to 8° 37' 30"E), with a total ocean area of about 185,100 km^2. The GoG region is a profitable fishing ground (Ocean Atlas, 2017) and home for many other aquatic species (NIMASA, 2018). The most important hydrographical regimes are the relatively stable thermocline, the steep temperature gradient, and stable oceanographic conditions below the mixed layer throughout the year. On an average, the SST is greater than 24°C, and the surface ocean is relatively warm during most part of the year (Ssentongo et al., 1986).

As shown in Figure 1, the study area is subdivided into three coastal regions: Lagos Lagoon location (3.625E, 6.375N), Niger Delta (Forcados) location (5.375E, 5.375N), and Cross River location (8.375E, 4.625N). With nearly equal areas of 771 km^2, each of the three locations was selected as being representative of a zone comprising an area of similar ecology and coastal processes.

The Lagos Lagoon location, which is characterized by lancets (*Branchiostoma)* that are tolerant to changes greater than average sea surface temperature range, experiences obliquely breaking waves that develop under the predominantly south-westerly winds (Webb, 1958; Smith, 1959). The lower reaches of the River Niger, exhibits a characteristic finger-shaped profile, with one of its branches, the Forcados River, emptying their waters and sediments into the Niger Delta location (blue box in Figure 1). With a total annual discharge of 21, 800 m^3, the oceanographic condition of this coastal area is largely affected by heavy loads of suspended sediments (Ssentongo et al., 1986). Abam (2001) revealed that this
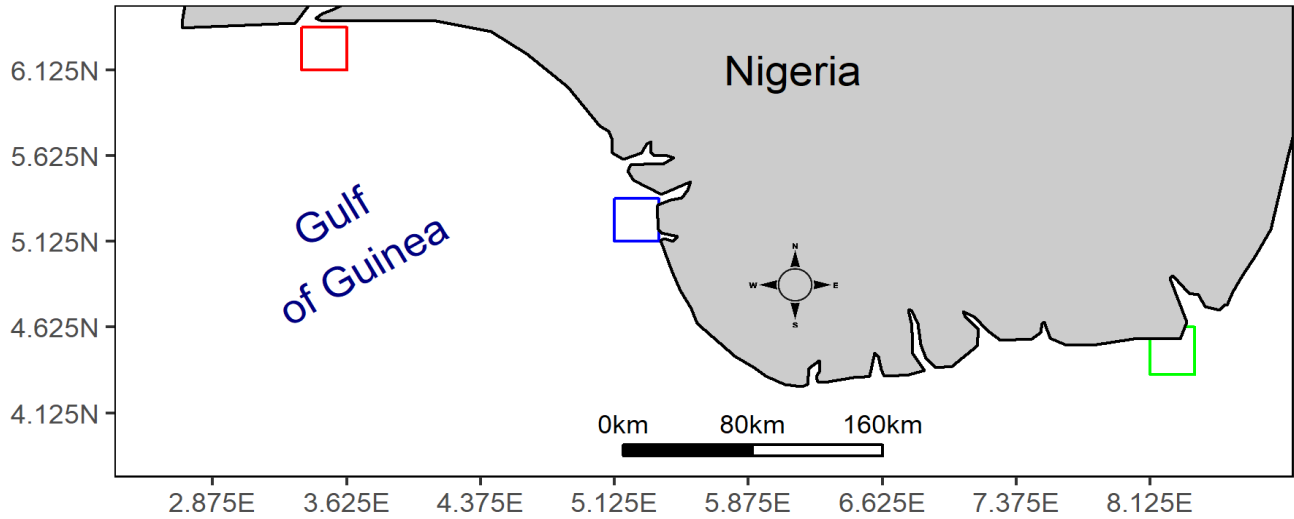
Figure 1. Map of the Nigerian coastline showing area of study. Red box - Lagos Lagoon segment; Blue box - Niger Delta (Forcados) region and Green box - Cross River segment.
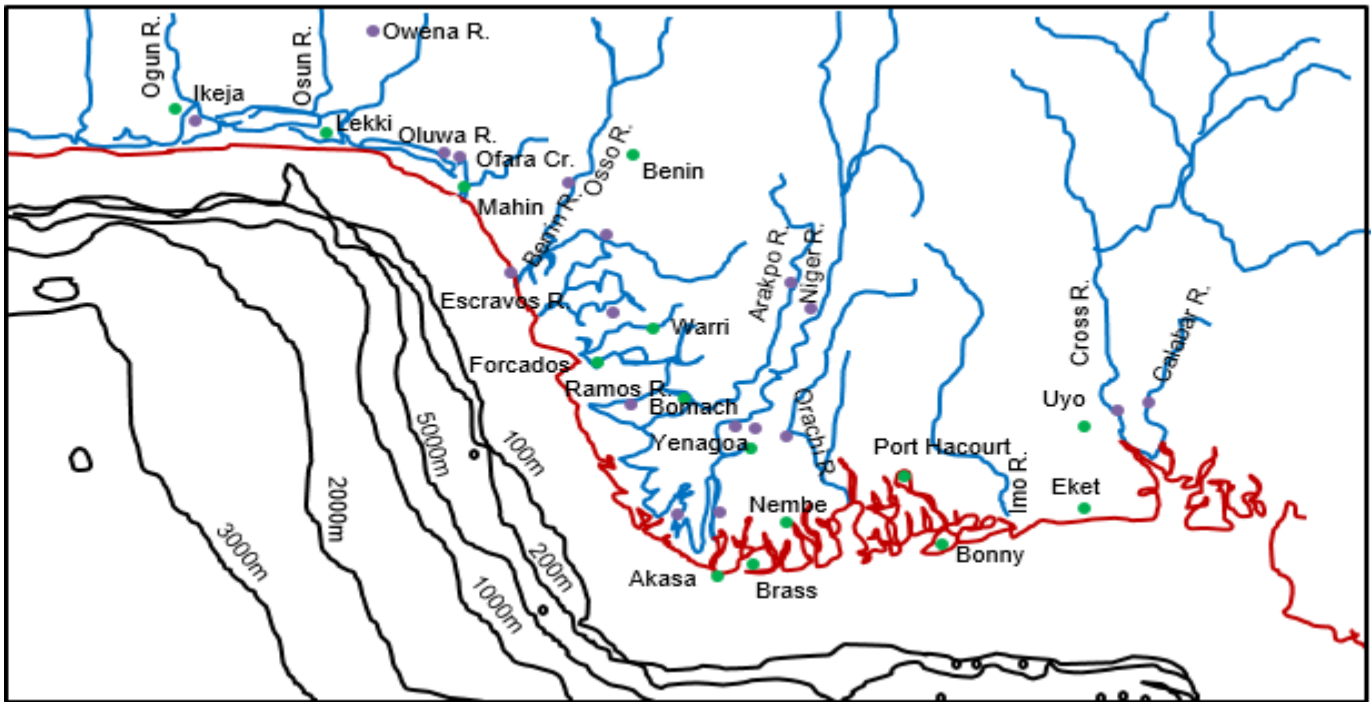

Figure 2. The bathymetric profile of the Nigerian coastal zone indicating the narrowing of the continental shelf at the Lagos zone (after Nwilo and Badejo, 2015).

location is dominated by a bidirectional tidal flow, while Ansa et al. (2015) concluded that the mouth of Forcados River has a stable plankton community structure that is comprised thirty two species. The Cross River is the main river in south-eastern Nigeria with 4 major tributaries namely the Calabar, Great Kwa, Mbo and Akpayafe Rivers draining through several kilometres of freshwater swamp before emptying into the Cross River estuary. The outer estuary enters the Gulf of Guinea at the Cross River location (green

box in Figure 1) with a much stronger current velocity of about 0.4 to 0.6 m/s further inland. Ssentongo et al. (1986) reported that this location and its surroundings have increasing fishing activities due to its higher productivity and high demersal fish stocks. The Nigerian continental shelf and the thermocline zone lies within the 40 m depth in the sub-surface and narrows towards the Lagos axis limiting the zone of fisheries and sea mining exploitation (Figure 2). The narrow continental shelf also influences the extreme

occurrence of plunging breaker waves compared to spilling breakers that are dominant along the mesotidal beaches of Ibeno beach at the Cross River segment (Asuquo, 1991; Nwilo and Badejo, 2015).

Acquisition of oceanographic data

Daily NOAA AVHRR-Only Optimum Interpolation Sea Surface Temperature (OISST) data at a spatial resolution of 0.25 degree in longitude-latitude coordinates for 30 years (1988 - 2017) period were obtained from the IRI/LDEO Data Library. The locations where data was collected to represent the GoG between latitudes 3° 52' 30"N to 6° 22' 30"N and longitudes 2° 37' 30"E to 8° 37' 30"E (Figure 1). At 0.25 degree (roughly at 28 km) intervals of longitude and latitudes, a total of 240 SST data points (24 longitude steps and 10 latitude steps) were extracted. However, due to the presence of land and the resulting absence of SST in these locations, only 161 data points were useful and realistic, including data points of the 3 focus coastal regions. Collected data set ranged between 22.51 and 36.65°C, and so the sourced dataset was reliable since it did not contain daytime unrealistic SST values (~40°C).

Hobday et al. (2016, 2018) proposed a hierarchical definition (Table 1) and categorization (Figure 3) of MHWs and this forms the central point of this study as an attempt was made to analyse daily SST data and detect MHWs that occurred over the entire study area.

The Gaussian or Normal distribution model is defined by the probability density function (PDF), where μ is the population mean and σ^2 is the variance:

$$f(x) = \frac{1}{\mu\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \tag{1}$$

The PDF is an exponentially decaying curve centred around μ and scaled by a factor. If a random variable X (e.g., sea surface temperature) follows the Gaussian distribution, then approximation:

$$X \sim N(\mu, \sigma^2) \tag{2}$$

The expected value of X is:

$$E[X] = \int_{-\infty}^{\infty} x f(x)\, dx \tag{3}$$

SST is known to exhibit slow variation over time and is therefore usually normally distributed (Burroughs, 1992). Hence, this model was used to understand the inter-annual distribution of maximum intensities exhibited by MHWs over each focused coastal region.

To determine and chart the trend of MHW frequency over the entire study area, Poisson regression model was used. This model is a generalized linear model (GLM) with the logarithm as the link function, and it is useful for analysing data in the form of discrete counts. The Poisson regression model is expressed as:

$$P(y_i = y \mid x_i;\ \beta) = \frac{e^{\left(-e^{(x_i'\beta)}\right)} e^{(x_i'\beta)y}}{y!} \tag{4}$$

Equation 4 is derived from the Poisson distribution and a parameterization that serves the purpose of linking the count variable y_i (MHW count), and the explanatory variable x_i (occurrence year). The regression coefficient with interest to be estimated is β, while the linear index is $x_i'\beta$ and

$$e^{(x_i'\beta)} \geq 0 \tag{5}$$

Kruskal-Wallis rank sum test was used to compare maximum intensities of MHWs, through the climate period, for the three coastal marine locations. This nonparametric test is a version of the independent measures (One-Way) ANOVA that can be performed on interval data. Finally, Kendall rank correlation test was performed to evaluate the association between MHW count and year of respective occurrence. The Kendall rank correlation coefficient or Kendall's tau statistic is also nonparametric, and can be used to test for monotonic trends or estimate a rank-based measure of association. With regard to the probabilities of observing the agreeable (concordant) and non-agreeable (discordant) pairs, the interpretation of tau is direct. All analyses were carried out using RStudio (version 1.1.453), a code editor and environment that runs the R language for statistics. Details of the R implementation of MHW detection (Schelegel and Smith, 2018) can be found in the package, heatwaveR (version 0.3.3), while more details on models and tests utilized in this study can be found in R's base package documentation or other statistics text.

RESULTS AND DISCUSSION

Detection of marine heatwaves

Based on the criteria of Hobday et al. (2016), 10,591 marine heatwaves were detected to have occurred between April 1988 and November 2017 in the entire study area (161 data points or grids). For Lagos Lagoon location (3.625E, 6.375N), 70 MHWs were detected and 9, 7, 10, and 8 of these occurred in 2010, 2015, 2016 and 2017, respectively. The longest MHW in this location lasted for 25 days in 2016 (23 October - 16 September), reaching a maximum intensity of 1.83°C on 31 October, and was classified as strong (Category II) for 20% of days. On the other hand, the most intense MHW (2.24°C) persisted for 20 days in 2007 (13 August - 1 September, with 26 August as peak date), and was classified as strong for 35% of its duration.

The Niger Delta location (5.375E, 5.375N) experienced 70 MHWs during the study period. However, 6 MHWs each occurred in these years: 2008, 2009, 2015, 2016, and 2017. The longest MHW observed lasted for 26 days (27 April - 22 May) in 2016, and had a maximum intensity of 2.05°C on 9 May. This was a strong MHW for 8% of its duration. The most intense MHW (2.66°C) in this study was classified as severe (Category III) for 5%, strong for 10%, and moderate for 86% of its 21 days duration (26 October - 15 November 2007). The peak date was 21 October, 2007.

The number of MHWs observed at the Cross River location (8.375E, 4.625N) was 78. Eight of these events occurred in 2016 alone, and 6 each in 1988, 2010, and 2017. Analysis shows that the longest MHW in this coastal region occurred in 2016 and lasted 28 days (16 June - 13 July), and reached a maximum intensity of 1.49°C on 28 June. Hence, it was classified as moderate. The MHW exhibiting the largest maximum intensity (2.83°C) in this location was classified as severe for 14%, strong for 64%, and moderate for 21% of its 14-day duration. This MHW occurred in 1998, from 1 to 14 February, and peaked on the 11th day.

Table 1. Hierarchical classification of metrics to define marine heat waves (MHW) after Hobday *et al.* (2016).

Metric level	Name	Definition	Equation	Unit
	Climatology	T_m: The climatological mean, calculated over an 11-day window.	$$T_m(j) = \sum_{y=y_s}^{y_e} \sum_{d=j-5}^{j+5} \frac{T(y,d)}{11(y_e - y_s + 1)}$$ where j is Julian day of the year, y_e and y_s are the start and end of the climatological base period, respectively, and T is the daily SST on day d of the year y.	°C
	Threshold	$T_\%$: The seasonally varying temperature value that defines a MHW. (T_{90} is the 90th percentile value based on the baseline period)	$$T_{90}(j) = P_{90}(X)$$ where P_{90} is the 90th percentile and $P_{90}(X)$ where $X = \{T(y,d) \mid y_s \leq y \leq y_e, j-5 \leq d \leq j+5\}$	°C
	MHW start and end dates	t_e, t_s: discrete dates on which a MHW starts and ends.	t_s is the time, t, where $T(t) > T_{90}(j)$ and $T(t-1) < T_{90}(j)$. t_e is the time, t, where $t_e > t_s$ and $T(t) < T_{90}(j)$ and $T(t-1) > T_{90}(j)$. For MHWs, $t_e - t_s \geq 5$, and where gap ≤ 2 days.	Days
Primary	Duration	D: Consecutive time period that temperature exceeds the threshold	$$D = t_e - t_s$$	Days
	Maximum intensity	i_{max}: highest temperature anomaly value during the MHW	$$i_{max} = \max(T(t) - T_m(j))$$	°C
Secondary	Spatial extent	A: Area of ocean meeting the MHW definition L: Length of coastline for the MHW	A = area over which MHW detected L = length of coast where MHW detected	km^2 km

Variation in monthly occurrence of marine heatwaves in the study area

The monthly pattern and distribution of MHW in the GoG are as shown in Figure 4. For the entire study area, maximum count and most pronounced MHW occurrence is in May (wet season) (Figure 4a), with a unimodal distribution. Comparatively, MHWs occurrence showed slight differences from May, as March and November followed as the second and third months, respectively for MHW occurrence. At the Cross River location, there is a conventional bimodal distribution (Figure 4b), MHW
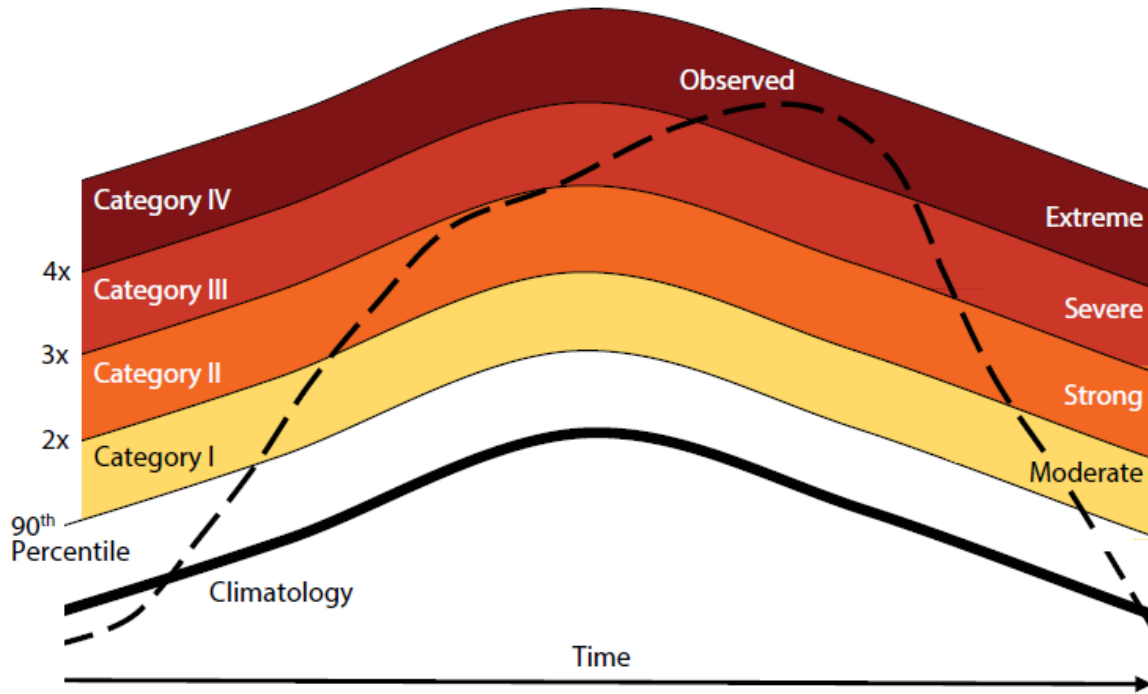
Figure 3. MHW categorization after Hobday et al. (2018). Observed temperature (dashed line), climatology (bold line), and the 90th percentile threshold (thin line) are illustrated. Multiples of the 90th percentile difference (2× twice, 3× three times, etc.) from climatology value define each of the categories I-IV, with corresponding descriptors from moderate to extreme.
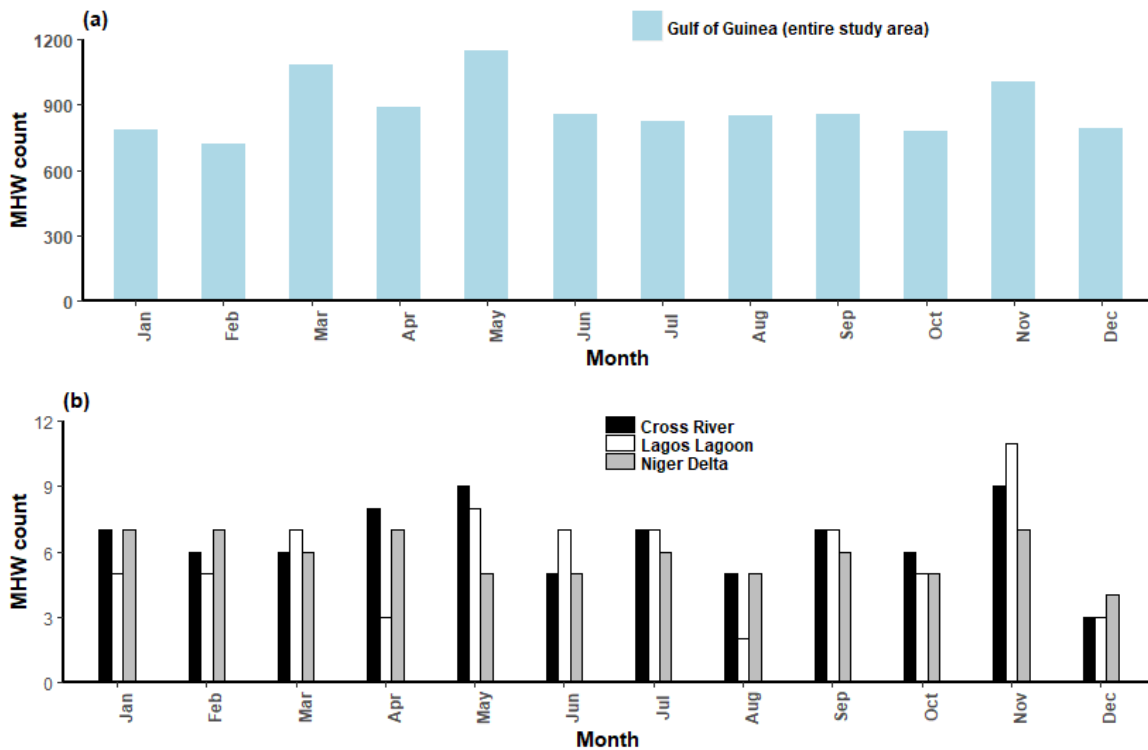

Figure 4. (a) Comparison of monthly MHW pattern over Gulf of Guinea (entire study area) and (b) focus coastal regions: Cross River, Lagos Lagoon, Niger Delta locations.

occurrence first peaks in May and then in November. This observed monthly pattern is comparable to that of the entire study area. Lagos Lagoon location is characterized by a unimodal distribution, with November as the peak for MHW occurrence. Comparison with other locations shows that even more MHWs occur in November at the Lagos Lagoon coastal region. Here also, there are substantial reductions in MHW occurrence in April, August, and December, all at a 3-month interval. A multimodal distribution is seen at the Niger Delta location, with January, February, April, and November, respectively as peak months for MHW occurrence.

November is shared as a peak month for MHW occurrence across the three focus coastal regions, while December is a common month for minimum MHW occurrence, except for Lagos Lagoon location. From July to December, the pattern per focus coastal region is homogeneous; simultaneously, there is a consecutive increase and decrease in MHW count.

The study area is permanently under the influence of the moist, warm, and unstable southwesterly monsoon trade winds, which replaces wintertime northeasterly Harmattan over the adjoining land area of Nigeria and West Africa in summer months from late-June to September. There is strong seasonality in the range of MHW count in the GoG (entire study area). Auxiliary analysis not presented in this study attributes this seasonality to an increased occurrence of Category III (severe) MHWs by approximately 400% during the traditional northern hemispheric winter months (October to May). There is a possibility that MHWs occur less frequently during summer months because coastal waters will be warmer, and incursions of offshore water, or atmospheric heating will not cause a significant difference in the expected daily temperatures to be defined as a MHW (Schlegel et al., 2017). Elsewhere, MHWs occurring in wintertime are known as winter warm spells, and are known to enhance colonization of marine invertebrates like sea urchins (Sherman, 2015; Wernberg et al., 2016).

MHW maximum intensity distribution over each focus coastal region

Gaussian normal distribution shows (Figure 5a) that maximum intensities of detected MHWs over the climate period (1988 to 2017) ranged from 0.89 to 2.83°C (Cross River location), 0.92 to 2.24°C (Lagos Lagoon location), and 0.94 to 2.67°C (Niger Delta location). The percentage of MHWs with maximum intensities of 1.95°C or more that occurred at the Cross River location is 10%. For Lagos Lagoon location, observed maximum intensities between 1.45 and 2.0°C corresponded to 48% of MHWs. While at the Niger Delta location, 56% of MHWs occurring had maximum intensities of 1.5°C or above. Right ends of the distribution curves of Niger

Delta and Cross River locations are farther out when compared with the Lagos Lagoon location, suggesting a unique reduction in maximum intensities of MHWs across considered locations along Nigeria's coastal zone. However, Kruskal-Wallis rank sum test reveals that there is no significant difference between the three locations on maximum intensities of MHWs experienced through the climate period, Chi-squared or χ^2 = 4.891 (degrees of freedom = 2, total sample size or N = 210), *p*-value > 0.05.

The curve of maximum intensities exhibited by MHWs in Lagos Lagoon location is symmetrical, and so normally distributed. The distribution curves of the other two focus coastal regions approach normality. Although SST is known to exhibit slow variation over time and is therefore usually normally distributed (Burroughs, 1992), the almost unnoticeable level of skewness in these other locations are expected since MHWs themselves are extreme events, and maximum intensities represent the highest temperature anomaly value during the duration of MHWs.

Using the scheme proposed by Hobday et al. (2018), the categorization of MHWs that occurred in the three coastal regions through the climate period is as shown in Figure 5b. Among these locations, no MHW was classified as Category IV (extreme). For preceding categories, there were striking reductions in number of MHWs across all three locations. Niger Delta and Cross River locations alone experienced MHWs classified as severe (Category III). Severe MHWs are relatively uncommon on a global basis, and associated with enervating ecological impacts. The 2003 Mediterranean MHW was severe, and biological studies revealed negative effects on as much as 80% of the Gorgonian fan colonies in the Mediterranean Sea, as well as mass bleaching and mortality (Garrabou et al., 2009; Crisci et al., 2011).

Long-term trend of the inter-annual occurrence of MHWs in the entire study area and monotonic trend detection in focus coastal regions

Mapping the estimated long-term trend of number of MHW occurrence per year, as calculated from the Poisson regression model, revealed significant increase over the entire study area mainly at 99% confidence interval as expected under climate change, with an exception for Cross River location. This, as well as the corresponding significance (*p*-value) of these trends per data point or grid is shown in Figure 6. The northwest area of the study area had higher MHW counts. Although normal occurrence of extreme events depends on multiple physical drivers, their increasing frequency can be linked to anthropogenic climate change (Trenberth et al., 2007; Cramer et al., 2014). Sylla et al. (2016) reported that a clear warming, statistically significant at the 90% level, is trending over most West Africa in recent
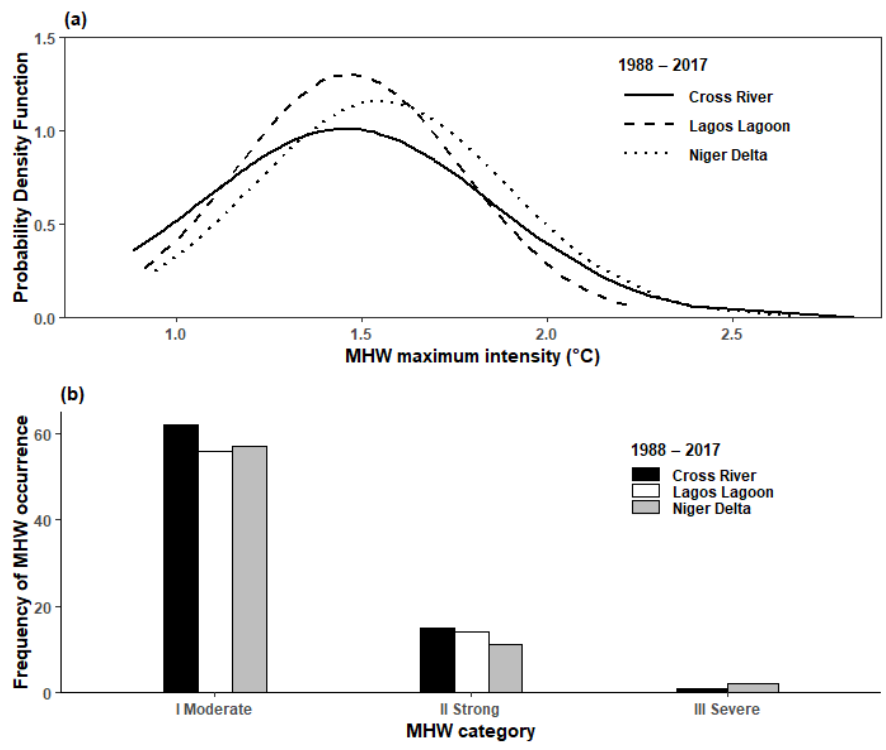
Figure 5. (a) MHW maximum intensity distribution over the three focus coastal regions during the climate period used. (b) Bar chart of number of events in each MHW category observed per focus coastal region.
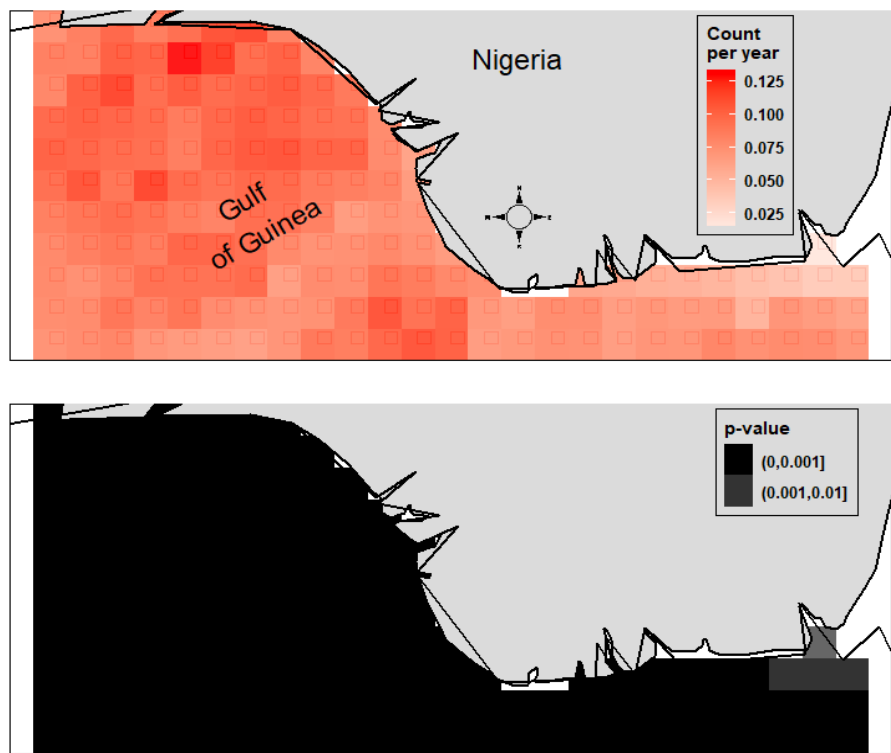

Figure 6. Map of the slope of the count of events detected per year during the period (top row). Map of the significance (p-value) of these trends in shades of grey (bottom row).

Table 2. (a) Result of Poisson regression and (b) result of Kendal rank correlation test.

(a) Result of Poisson regression					
Focus coastal region	Estimated model $\log(y_i) = c + \beta\ x_i$ y_i is MHW count, x_i is occurrence year, β is regression coefficient c is slope	Asymptotic standard error for estimated regression coefficient (β)	z-value	p-value (significant at 0.05)	Ratio of the value of the residual deviance statistic to the degrees of freedom
Cross River location	$\log(y_i) = -35.21476 + 0.01806x_i$	0.01318	1.370	0.171	1.629
Lagos Lagoon location	$\log(y_i) = -204.09600 + 0.10216x_i$	0.01698	6.015	1.80e-09	2.012
Niger Delta location	$\log(y_i) = -135.92637 + 0.06822x_i$	0.01524	4.475	7.63e-06	1.644

(b) Result of Kendall rank correlation test		
Focus coastal region	Tau	p-value
Cross River location	0.12	0.3602
Lagos Lagoon location	0.46	0.0007813
Niger Delta location	0.44	0.001506

decades. Also, the GoG and west Sahel region experience the most significant and warmest signals ranging from 0.2°C to more than 0.5°C per decade. Mean warming in the ocean due anthropogenic climate change and not SST variance drives marine heatwave trends (Oliver, 2019). The current trend in global warming does not inevitably mean that occurrence frequency of MHWs will increase rapidly; however, where climate systems shift from historic records, increases in MHWs will likely occur (Schlegel et al., 2017). Simulations done by Oliver et al. (2017) indicate that MHW event likelihoods will increase in the future, due to increasing anthropogenic influences.

Table 2 gives the estimated model and other relevant details for the three focus coastal regions. Except for Cross River location, the predictor (occurrence year) and slope of the model is statistically significant given corresponding z-values and low p-values. However, considering the ratio of the value of the residual deviance statistic to the degrees of freedom which is higher than unity, the model fit can be improved by including other explanatory variables. For example, these could include patterns of prevailing southwesterly winds and the Guinea Current; seasonal cycle of surface air temperature and pressure; and correct representations of climatological anomalies such as the Dahomey Gap, geophormology of the Nigerian continental boundary, and the GoG basin. A seasonal variability in wind and current patterns was central to the formation of coastal MHWs around southern Africa (Schelegel et al., 2017), while the main driver of the "Blob" off the Pacific Northwest was surface pressure (Bond et al., 2015), and eddy kinetic energy (EKE), was a primary driver of the 2015/2016 Tasman Sea MHW (Oliver et al., 2017).

Since estimate of $\beta > 0$, the more the years, the greater expected number of marine heatwaves on the multiplicative order as $exp(0.10216) = 1.11$ for Lagos Lagoon location and as $exp(0.06822) = 1.07$ for Niger Delta location. More specifically, for one unit of yearly increase, the number of *MHWs* will increase and it will be multiplied by 1.11 and 1.07 for Lagos Lagoon and Niger Delta locations, respectively.

Kendall rank correlation test result (Table 2) shows that MHW count and occurrence year significantly have a moderate positive correlation in Lagos Lagoon and Niger Delta locations at 95% confident interval. This is supported by the monotonically increasing trends as shown by the Trend line and Loess curve fit in Figure 7. For Cross River location, Kendall's tau suggests a weak association between MHW count and occurrence year, but this is not significant (p-value > 0.05) as a nonmonotonic trend is observed.

Conclusion

The analyses of daily sea surface temperature (SST) through a period of 30 years in the Gulf of Guinea (GoG) region bordering Nigeria show the occurrence of marine heatwaves (MHWs) since 1988. MHWs occurred more frequently in the northwest region of the study area. Three focus coastal regions were also considered based on ecology and coastal processes: Cross River location, Lagos Lagoon location, and Niger Delta location. As expected under climate change, there is also a positive correlation between MHW count and occurrence year. However, this increasing frequency is not significant inCross River location alone. Higher frequency does not necessarily mean susceptibility to stronger impacts on fishing zones and local ecosystems, and consequently, the human populations dependent on them for food and livelihood. Maximum intensities characterizing MHWs is a
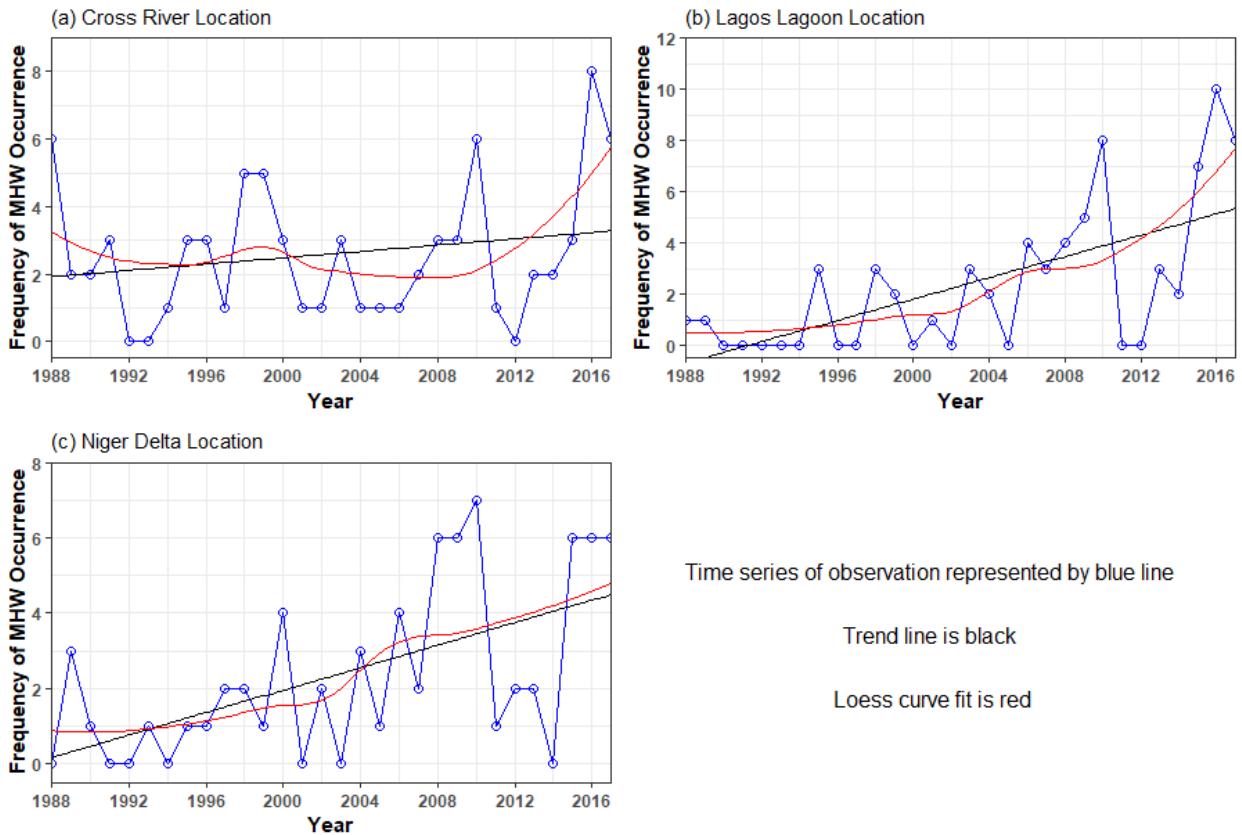
Figure 7. Trend of MHW frequency across focus locations (Lagos Lagoon, Cross River, and Niger Delta) during the climate period; 1988 to 2017.

better and sophisticated measure for this. There was no significant difference across the three focus coastal regions on maximum intensities of MHWs experienced through the climate period, though Cross River and Niger Delta locations experienced severe MHWs; the highest category observed between the three locations. MHWs were mostly detected in May for the entire study area. Though multiple peak months are only observed in Cross River and Niger Delta locations; all three focus coastal regions share November as a peak month. There is strong seasonality in MHW occurrence in the entire study area, and this is attributed to an increased occurrence of Category III (severe) MHWs during traditional northern hemispheric winter months (October to May).

There is still a knowledge gap on what detected MHWs meant for the GoG. Hence, it is recommended that biological and socioeconomic assessment relevant for this area should be conducted. The abundance and distribution of economical fish and shrimp species and, probably the appearance of uncommon species and alterations in ecological conditions of Nigeria's coastal waters should be documented and monitored, including via citizen science which helps engage and inform policy makers and public of vulnerability to climate change-driven extreme events. Further physical studies are also

needed to determine drivers for MHWs in this region, as well as understand other characteristics such as duration, rates of onset and decline.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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