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Assessing the Variability of Extreme Weather Events and Its Influence on Marine Accidents along the Northern Coast of Tanzania

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Abstract

The marine accidents are among the main components of the Zanzibar Disaster Management Policy (2011) and the Zanzibar Blue Economy Policy (2020). These policies aimed to institute legal frame works and procedures for reducing both the frequency of marine accidents and their associated fatalities. These fatalities include deaths, permanent disabilities and loss of properties which may result into increased poverty levels as per the sustainable development goal one (SDG1) which stipulates on ending the poverty in all its forms everywhere. Thus, in the way to support these Government efforts, the influence of climate and weather on marine accidents along Zanzibar and Pemba Channels was investigated. The study used the 10 years (2013-2022) records of daily rainfall and hourly wind speed acquired from Tanzania Meteorological Authority (TMA) (for the observation stations of Zanzibar, Pemba, Dares Salaam and Tanga), and the significant wave heights data, which was freely downloaded from Globally Forecasting System (GFS-World model of 13 km resolution). The marine accident records were collected from TASAC and Zanzibar Maritime Authority (ZMA), and the anecdotal information was collected from heads of quay and boat captains in different areas of Zanzibar. The Mann Kendal test, was used to determine the slopes and trends direction of used weather parameters, while the Pearson correlations analysis and t-tests were used to understand the significance of the underlying relationship between the weather and marine accidents. The paired t-test was used to evaluate the extent to which weather parameters affect the marine accidents. Results revealed that the variability of extreme weather events (rainfall, ocean waves and wind speed) was seen to be among the key factors for most of the recorded marine accidents. For instance, in Pemba high rainfall showed an increasing trend of extreme rainfall events, while Zanzibar has shown a decreasing trend of these events. As for extreme wind events, results show that Dar es Salaam and Tanga had an increasing trend, while Zanzibar and Pemba had shown a decreasing trend. As for the monthly variability of frequencies of extreme rainfall events, March to May (MAM) season was shown to have the highest frequencies over all stations with the peaks at Zanzibar and Pemba. On the other hand, high frequency of extreme wind speed was observed from May to September with peaks in June to July, and the highest strength was observed during 09:00 to 15:00 GMT. Moreover, results revealed an increasing trend of marine accidents caused by bad weather except during November. Also, results showed that bad weather conditions contributed to 48 (32%) of all 150 recorded accidents. Further results revealed significant correlation between the extreme wind and marine accidents, with the highest strong correlation of r = 0.71 (at $p \leq 0.007$) and r = 0.75 (at $p \leq 0.009$) at Tanga and Pemba, indicating the occurrence of more marine accidents at the Pemba channel. Indeed, strong correlation of r = 0.6 between extreme rainfall events and marine accidents was shown in Pemba, while the correlations between extremely significant wave heights and marine accidents were r = 0.41 (at $p \leq 0.006$) and r = 0.34 ($p \leq 0.0006$) for Pemba and Zanzibar Channel, respectively. In conclusion, the study has shown high influence between marine accidents and bad weather events with more impacts in Pemba and Zanzibar. Thus, the study calls for more work to be undertaken to raise the awareness on marine accidents as a way to alleviate the poverty and enhance the sustainable blue economy.

Keywords

Marine Accidents, Bad Weather Events Extreme Wind Speed, Extreme Rainfall, Correlation

1. Introduction

It is a well-known fact that the maritime industry contributes significantly to the socioeconomic growth of many nations that are bordered by the sea or have interior water bodies including lakes and rivers (Li et al., 2023). However, a variety of factors have an impact on maritime economic development. Among the things that make maritime labor challenging is the occurrence of bad weather conditions which normally worsens the ocean states. The most important concern of our days is climate change, which has an unparalleled global reach and is linked to changing weather patterns that endanger human lives and the global economy. The escalating frequency and intensity of extreme weather events linked to natural disasters is one sign of climate change (Koesharyani et al., 2018). These occurrences have an impact on numerous aspects of human existence, including the maritime environment, and cause major property damage and loss, endangering socioeconomic progress and leading to increased poverty levels (Jahn, 2015). Additionally, the number of fatalities and casualties from these events interrupts livelihoods and income-generating activities, which has long-term impacts on people's well-being and future human capital development. The global records show that the marine industry (sector) has inured about 8835 disasters which resulted in 1.94 million fatalities and cost about $2.4 trillion to resolve these fatalities, with the main contributors of these disasters being extreme weather (IPCC, 2022). Studies including [5] have noted that both meteorological and hydrological factors have a significant connection with these catastrophic weather events. The marine sector, which mostly takes place in oceans (i.e. covers 71% of the earth's surface) and great lakes, is the most important in the global blue economy, with marine activities including fisheries, transportation and trade employing significant number of global population (Salby, n.d.). In Africa, maritime transportation and shipping is very important, as noted by [7] that over 90% of Africa's imports and exports are conducted via the ocean environment. The International Chamber of Shipping (ICS), and other organizations, have noted that the African continent accounts for 5% of the global marine import and export by volume while the shipping industries export about 90% of the world's trade in goods (Charter, n.d.). Moreover, reference [9] has concluded that about 820 million people are living through harvesting, processing, marketing, and distribution of various marine products Also, studies have shown that over 3 billion people depend on marine resources to sustain their livelihood. Besides, approximately 50% of all international tourists visiting the coastal areas, including the Small Island Developing States (SIDSs), make use of marine resources and contribute to about $3 - 6 trillion per year (Nations & On, 2009).

As for Tanzania, the marine sector contributes to about 4.5 million jobs of which 35% of rural employment indirectly depends on fishing activities (Jiddawi et al., 2002) while those directly depend in fishing are about 200,000 (Peart et al., 2021) and the sector contributes to about **1.75%** to Tanzania's gross domestic product (GDP) (MLF, 2020) Despite the country's low consumption of fish, at 5.6 kg/person/year, fish makes up 19.7% of the country's animal protein intake (Meeting Report for the Swiofc Nairobi Convention Partnership, 2022).

In combating the safety based on marine accidents and other environmental hazards the Revolutionary Government of Zanzibar (RGoZ) has established the Zanzibar Disaster Management Commission (ZDMC) under the second vice presidents office (VPO2) under the ACT No.1 of 2015 as per the requirement of the Zanzibar Disaster Management Policy (2011) as a result of the Zanzibar Disaster Risks and Capacity Needs Assessment of 2008 which showed that disasters including floods, marine accidents, epidemics, drought, environmental degradation, and strong winds causes great losses to live, property and environment and thus may push several people and a country into social and economic grief. The economic impact of disasters usually consists of direct damage e.g. infrastructure, crops, housing, and indirect damage e.g. loss of revenues, unemployment and market destabilization (Iii Zanzibar Disaster Management Policy, n.d.). The policy aimed at setting administrative and operational mechanisms towards building resilient communities by enhancing the use of and access to knowledge and resources in disaster prevention, mitigation, preparedness, response and recovery at all levels in the country. Also policy calls for deliberate efforts to ensure that development does not increase the country's susceptibility to disasters and thus it clearly paves the way for ensuring that we attain Vision 2020, and millennium development goals in sustainable manner (Iii Zanzibar Disaster Management Policy, n.d.). Also the Policy directs the Tanzania Meteorological Authority (TMA) Zanzibar Zonal office to forecast, monitor and disseminate the forecasts and early warning information on potential hazardous weather to other institutions and population at risk; Also the Zanzibar Blue Economy Policy of 2020 supplements the efforts of the ZDMC by aiming to work in prioritized areas including fisheries and aquaculture, maritime trade and infrastructure, energy, tourism and marine and maritime governance. These sectors were selected to increase employment, improve the balance of trade, promote food and nutritional security and maintain environmental resilience. However, the aforementioned (RGoZ, 2020) initiatives are engulfed by what happens in practical aspects on the ocean. In Zanzibar, apart from marine transportation, the marine sector is very useful in fishing activities which is mostly practiced by using small and weak gears (machines and the vehicles such dhows cannons among others) (Feidi, 2005) which are highly affected during bad weather and worsening ocean states. Also the TMA on the other hand issues and disseminate the daily weather forecasts and early warnings in case of strong winds, heavy rainfall and worse ocean states. Irrespective of all the undertaken initiatives but the trend and frequency of marine accidents associated with severe weather events are increasing. These are some highlighted examples of marine accidents taken place in Zanzibar and Pemba channels On October 2009 the marine vessel MV Faith capsized near the port of Malindi, resulting in 9 fatalities, also on 4th January, 2022 nine individuals lost their lives when local boats from Chokocho to Kisiwa Panza on Pemba Island capsized. Moreover on 22nd June, 2022, a fishing boat named "Ndiodunia" capsized in the Nungwi-Tanga channel with four fishermen on board. Indeed, on 25th November, 20211 a fishing boat named as Firdausi capsized at Zanzibar channel due to strong winds and causing a death of 11 people. Though policy infrastructure and legal frame works are in place, but currently accidents are increasing, and on the other hand there exists either no or limited documentations on understanding the impact of severe weather related marine accidents. These circumstances demand a well-managed, planned, and efficient system that aims to increase safety and decrease accidents. The primary goal of this study was to assess how, and to what extent, the variability of extreme weather events affects marine accidents in the Zanzibar and Pemba channels. Specifically, the study aimed to 1) analyze the trends and/or variability of extreme weather events including wind, rainfall and oceanic wave heights in Zanzibar and Pemba Channel, 2) access the influence of extreme wind and oceanic waves on marine accidents, and lastly 3) examine the underlying relationship between heavy rainfall and marine accidents. The paper is composed of four sections of which the second describes the data, study area and the analytical methods used; the third section presents the results for all stated specific objectives and the last section presents the conclusions and recommendations.

2. Methods

2.1. Study Area

The study was conducted in coastal Tanzania particularly the Zanzibar and Pemba channels which are located in the Southwestern Indian Ocean (SWIO) or over the South-eastern Africa. Zanzibar channel divides Tanzania's mainland from the island of Unguja, better known as Zanzibar. The channel is between 29 and 37 kilometers wide and 120 kilometers long. Its depth ranges from a few meters in the middle to a few hundred meters to the north and south. The southern entrance to the channel is indicated by a lighthouse located on the mainland coast 22 km south of Dar es Salaam at about 6˚S and 39˚E (Watkiss et al., 2012) and lies on the continental shelf of the coastal ocean of Tanzania between the mainland and Zanzibar Island (Watkiss et al., 2012). Like the Zanzibar channel, Pemba Channel separates the northeastern coast of mainland Tanzania on the coast Tanga region and western side of Pemba Island. The channel is located in northern Tanzania in the northern part of SWIO with 50 km wide and about 1000 m deep (Watkiss et al., 2012). The channel has steep bathymetry and a northward flowing current during June, July and August (JJA) and southward during October November and December (OND) rainfall season. Also the channel is located in a latitude and longitude range of 5.2˚S, 39.3˚E. The study area (northern coastal area of Tanzania) experiences pleasant weather throughout the year, warm tropical conditions, warm water, and perfect beaches (Msemo et al., 2021). The study area has two rainy seasons of March to May (MAM), locally known as *Masika,* which is characterized by abundant long rains with good spatial distribution, with wet, humid, and primarily cloudy conditions, and OND locally known as *Vuli*, and is characterized by less abundant short rains with poor temporal and spatial coverage (Kai et al., 2021a), The *Vuli* short rains season is followed by a dry season that is warm, windy, and primarily clear (Kai et al., 2021a), except during the active tropical cyclone season, strong El Nino and positive Indian Ocean Dipole (IOD) events and or off season rainfalls of January to February (Kai et al., 2021a; Kai et al., 2021b; Kai et al., 2021c). The coastal area of Zanzibar has warm and saline water and average sea surface temperature of 28˚C - 30˚C (McClanahan, 1988) (Khamis et al., 2017). Seasonal variations in the local monsoon wind can be found in the channels, where the peak of northeast monsoon season extends from October, December to February and the southwest monsoon season runs from April to December (Luis, 2014) (Mahongo et al., 2012) (**Figure 1**).

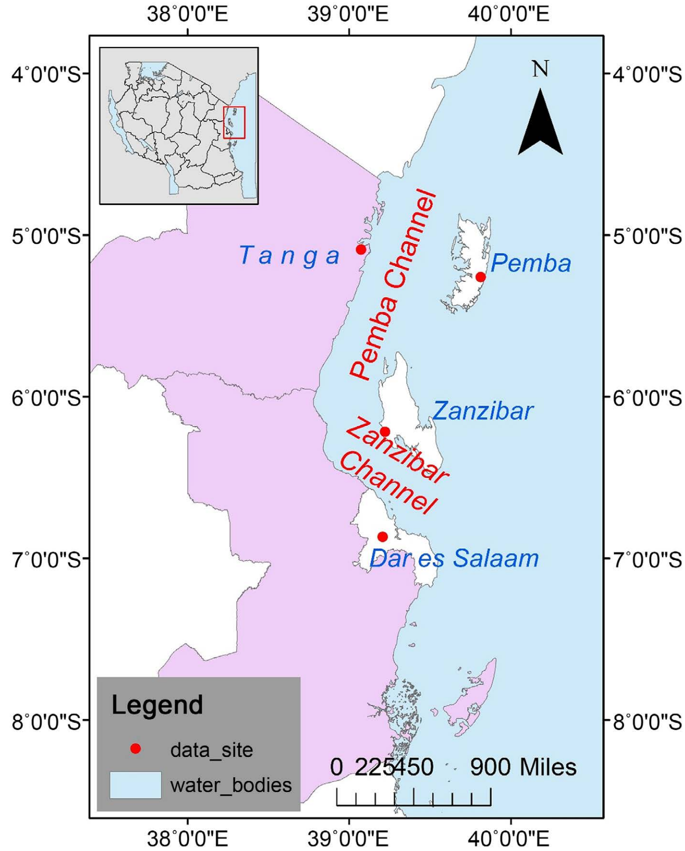


Figure 1. Map of study area (Source; Modified GIS Layer of Tanzania).

2.2. Datasets

The study used three types of datasets, including: 1) Climatic data (wind speed, rainfall) which were acquired from Tanzania Meteorological Authority (TMA), Zanzibar office, and oceanographic parameters of significant wave height which was downloaded in the ocean waves, GFS model (GFS-World of 13 km resolutions). The temporal resolution of the climate parameters including daily wind speed and monthly rainfall datasets for the northern coast of Tanzania was 10 years (2013-2022). These datasets were collected in four meteorological observation stations of Zanzibar, Pemba, Tanga and Dar es Salaam. The significant wave heights was downloaded from the GFS model at the centers of Nungwi (for Pemba channel) and Zanzibar port for Zanzibar channel, respectively. 2) The 13 years (2009 to 2022) marine accident datasets were collected from Tanzania Shipping Cooperation (TASAC) database and Zanzibar Maritime Authority (ZMA). The ZMA and TASAC datasets contain the information for the occurrence of an accident (date and time (day/night)) as well as locations (longitude and latitude), causes of that accident, summary of the accident and casualty types, name and type of the vessels. Based on the locations indicator the acquired marine accidents datasets have recorded 150 accidents. These accidents were incurred by vessels which were sailing along the northern cost of Tanzania passing through Zanzibar and Pemba Channels. As for the causal conditions of these accidents the data shows that the main causal factors were bad weather conditions, breakdown, flooding, fire, collisions, overloading as well as engine problems. Since the study focus was on the accidents which occurred during bad weather events and poor ocean conditions, all cases with descriptions other than weather conditions were filtered out. 3) The primary data i.e., anecdotal information was obtained through interview and focused group discussions with the head of quay and dhow operators (boat captains) from different landing sites of Unguja Island. These landing sites includes Mkokotoni, Nungwi, Malindi, Mazizini, Nyamanzi, Fumba, Unguja-Ukuu and Kizimkazi, respectively.

2.3. Trend Analysis Test

The climate and accidents data was tested for the trend using the Mann-Kendall test. This test is non-parametric and is widely used in detecting trends of monotonic variables in most fields including meteorology and hydrology (Wang et al., 2019). Equations (1)-(4) were used for identifying the trends of weather parameters.

$$S = \sum_{k=1}^{n-1} \sum_{k+1}^{n} \operatorname{sgn}\left(x_i - x_k\right) \tag{1}$$

where n is the length of the time series, x_i and x_j are the sequential data values, and S is a statistic, sgn() is defined as

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{cases} +1, \text{if } \left(x_j - x_k\right) > 0 \\ 0, \text{if } \left(x_j - x_k\right) = 0 \\ -1, \text{if } \left(x_j - x_k\right) < 0 \end{cases} \tag{2}$$

The variance of the S statistic (Var(S)), which is determined by the independence and regularly distributed nature of the data, is provided by

$$\operatorname{var}(s) = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

The test statistics Z will be computed by

$$z = \begin{cases} \dfrac{s-1}{\sqrt{\operatorname{var}(s)}}, \text{if } s > 0 \\ 0, \text{if } s = 0 \\ \dfrac{s+1}{\operatorname{var}(s)}, \text{if } s < 0 \end{cases} \tag{4}$$

The very high positive value of Z it will indicate increasing trend and the very high negative value of Z it will indicate decreasing trend.

2.4. Correlation Analysis

The technique used to examine relationships between the variables under study was correlation (Senthilnathan, 2019). Additionally, Wilks (2006) noted that correlation is a straightforward method for comparing dependent and independent variables. Extreme wind and rainfall frequency statistics were correlated with marine accident frequency data collected monthly and annually. The correlations formula is shown below:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \tag{5}$$

where

r is the Pearson correlations coefficient, $\bar{x}$ is the mean of variable x, $\bar{y}$ is the mean of variable y, x_i is the value of x variable (frequencies of accident data) and y_i is the value of y variable (frequencies of Extreme wind and Extreme rainfall).

2.5. t-Test Analysis

The statistical significance of the computed correlation value was tasted using t-test analysis by using confidence level 95%. The t-test formula is presented in Equation (6)

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{6}$$

where; r is the Pearson correlations coefficient and n is the number of observations.

3. Results

3.1. Extreme Rainfall Variability

The results of the analysis of the variability of the frequency of extreme rainfall events presented in **Figure 2** (blue bars) show that the months of March, April, and May had the highest incidences (19 - 20) of extreme rainfall events. This could be attributed by the fact that MAM seasons are characterized by long and heavy rain over the northern coastal areas of Tanzania including Unguja and Pemba with the highest rainfall during April in Unguja and during May for Pemba (**Figure 2** blue bars), this findings are in agreement with reference (Kai et al., 2021a) who noted that heavy MAM rains in Unguja occurs in April while that of Pemba in May. Moreover, results in **Figure 2** show that, for all investigated stations, the highest frequencies of extreme rainfall events were featured in April (i.e. 23 events) and May (i.e. 24 events) for Zanzibar and Pemba, respectively. The observed variability of the extreme rainfall events is well supported by the IPCC statement that Island areas are more affected by climate change effects and one among the indicator is the increase in the period of extreme weather events. In addition, results revealed that, during the months of June through September extreme rainfall events declined, indicating no records of extreme rainfall events during this period. Further results have shown the months October to December to be another period having high frequency of extreme rainfall events. This could be attributed to the fact that over the northern coastal Tanzania this period is characterized by the short rainfall season (*Vuli*) which is more convective oriented, and hence more common for the occurrence of extreme rainfall events.

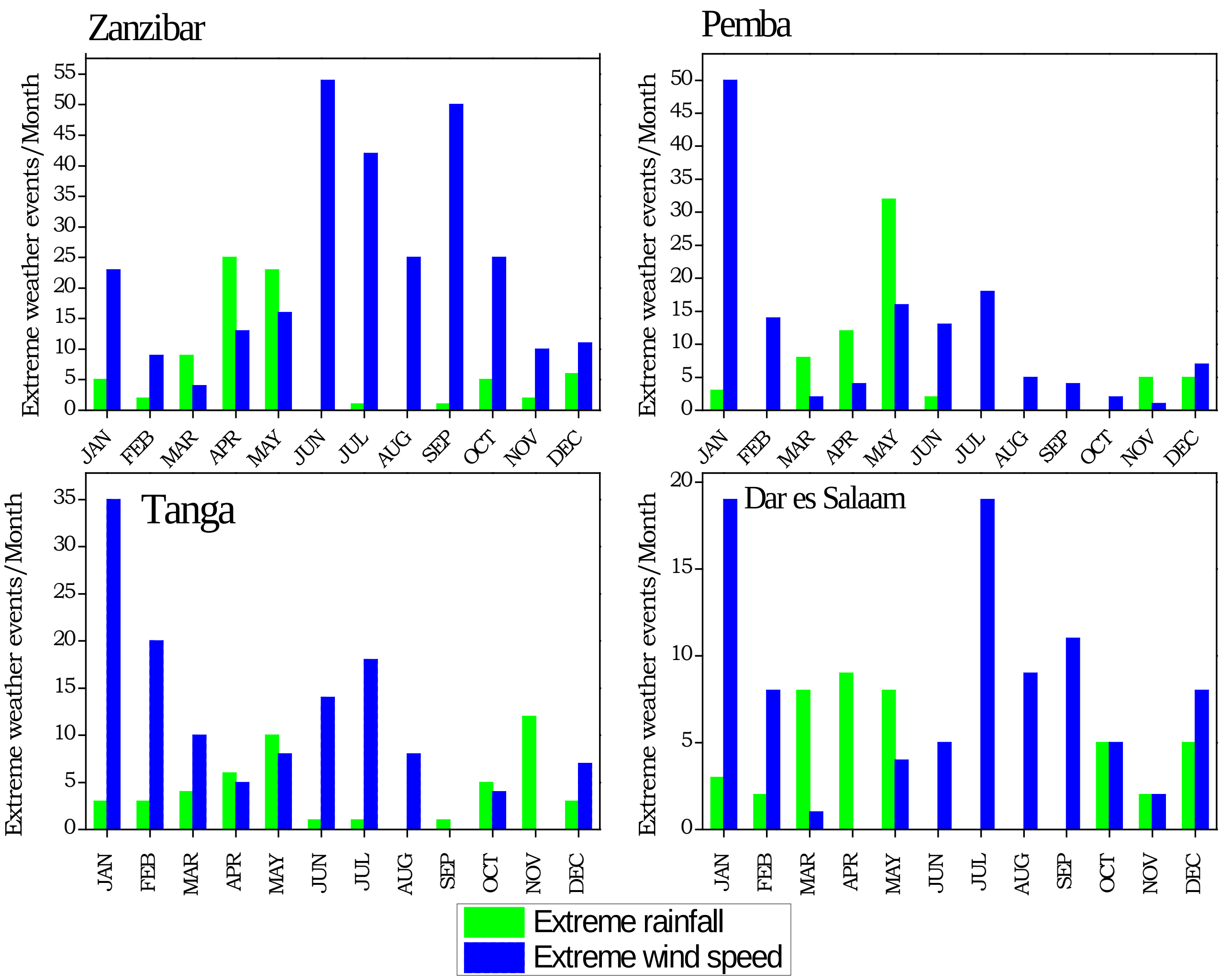


Figure 2. Monthly distribution of the frequencies of extreme rainfall (blue bars) and wind (green bars) events for observation stations of Zanzibar, Pemba, Dar es Salaam and Tanga.

As for the frequencies of extreme wind speed events, **Figure 2** (green bars) shows that highest frequencies occurred in Zanzibar with peak frequencies in June through September. Generally, for all investigated stations, the highest frequencies of extreme wind speed events occurred during January and then decreased during February to April, and then increased from June to September. This finding is supported by the state of the climate of Zanzibar which maps the strong winds during South East (SE) monsoons with the peak during June to July, the phenomenon which can be explained by the intensification of the Mascarene high pressure cell which pushes the huge mass of water into the Zanzibar channel resulting in strong winds and waves as supported by (Mahongo et al., 2012) and noted by (Kai et al., 2021a).

3.2. Hourly Variability of Extreme Wind Speed

The results of the hourly variability of extreme wind strength presented in Figure 3 shows that higher extreme wind events occurred during the day, with the maximum numbers of these events attained between 09:00 and 15:00 GMT, followed by a marked fall in frequencies between 18:00 and 21:00 GMT, and then followed by a steady rise between 06:00 and 09:00 GMT. More results in Figure 3 reveal that the period from 21:00 to 03:00 GMT, is characterized by low frequencies of extreme wind speed with the minimum frequencies during at 00:00 GMT; the peak extreme wind frequency occurred at 12:00 GMT and the lowest frequencies were in Pemba. That can be linked with insolation, where the maximum insolation in Zanzibar occurs at the mentioned periods.

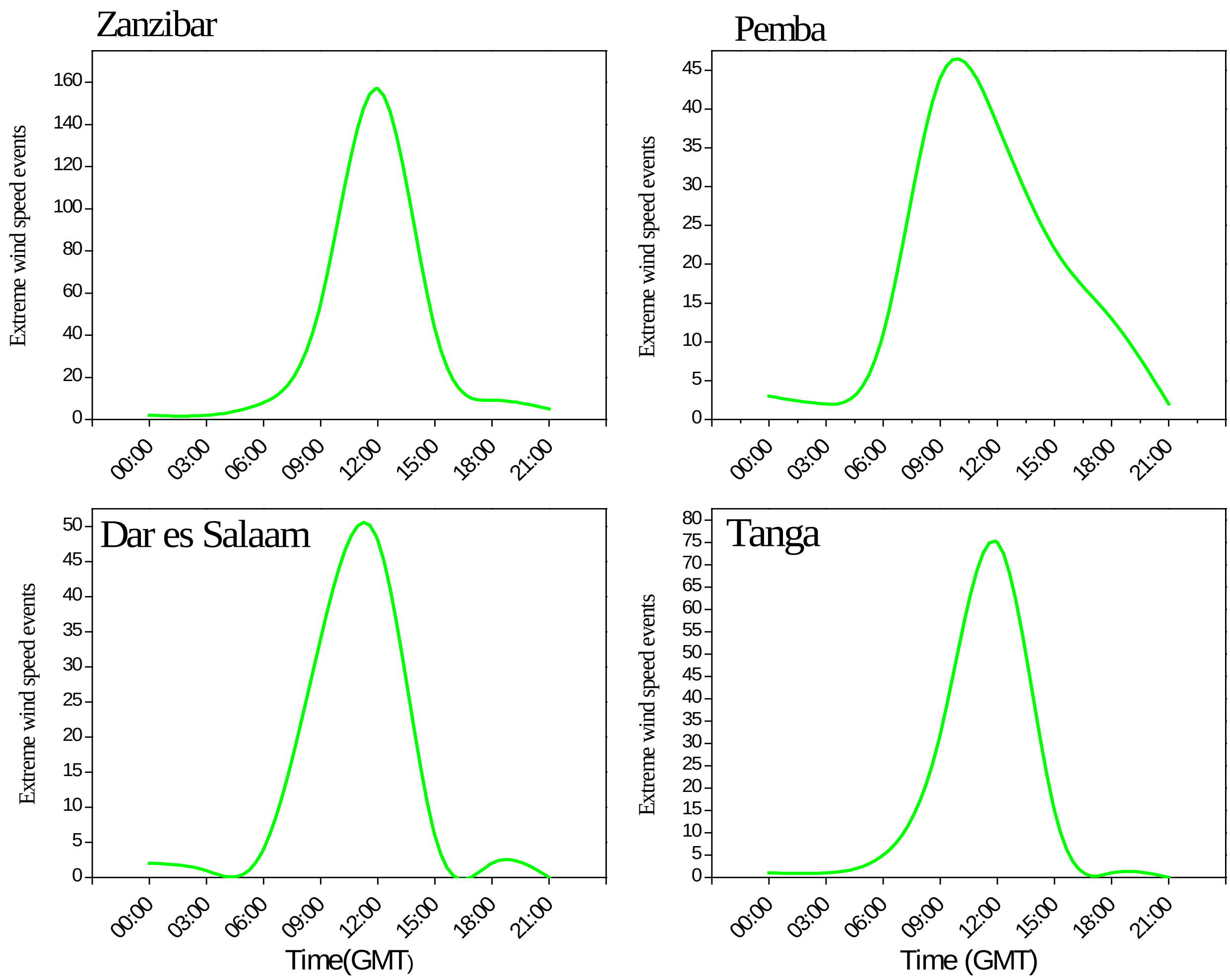


Figure 3. Hourly variability of extreme wind events from 2013 to 2022 for the investigated stations of Zanzibar, Pemba, Dar es Salaam and Tanga.

3.3. Variability of Significant Wave Heights

Monthly distributions of the frequencies of extreme significant wave height along Pemba and Zanzibar channels are presented in Figure 4. The results have shown that the extreme waves generally rise up from May to September with the highest peaks during June to July for both Channels. The number of significant extreme wave heights decreases during October to December with lowest peaks during December in both Pemba and Zanzibar channels. The frequency of extreme waves increases again in January before a marked fall in the month of March. This is due to the variability of extreme wind speed events during that months.

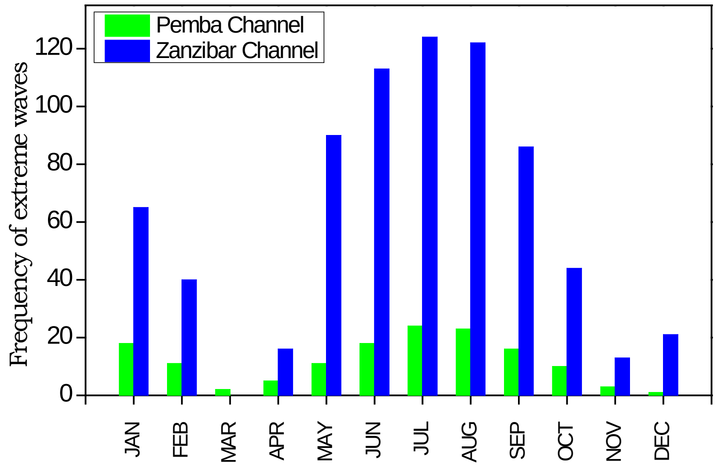


Figure 4. Monthly Distributions of extreme significant wave heights along Zanzibar (green) and Pemba (blue) Channel.

3.4. Trend and Variability of Extreme Weather Events

The annual variability of the frequency of extreme rainfall events results in Figure 5 revealed higher frequency of extreme rainfall events observed in three consecutive years of 2017, 2018 and 2019. This could be explained by the fact that over all investigated stations the period was characterized by severe ocean states. Additionally, the findings revealed that Pemba and Zanzibar stations observed the highest frequencies of extreme rainfall event, whereas Dar es Salaam had the lowest frequency. In contrast, the variability of extreme wind speed events in Figure 5 (green bars) has revealed that the highest peaks occurred at Zanzibar in the years 2021 and 2022 (55 and 65 events, respectively); in Pemba during 2016 and 2022, and also in Tanga stations for three consecutive years in 2020, 2021, and 2022. Except for 2021, which had the greatest peak frequencies of 34 incidents, Dar es Salaam station was characterized by the lowest values of extreme wind events in several of the years under investigation. Moreover, results in Figure 5 reveal that, for the Zanzibar station, extreme wind events increased at a rate of 0.5/year, while extreme rainfall events declined from 2013 to 2022 at a rate of −0.1/ year. On the other hand, in Pemba the rate of extreme rainfall events fell from 2013 to 2022 at a rate of −0.5 events/year, whereas the rate of extreme rainfall events increased at a rate of 0.5 events/year. As for Tanga and Dar es Salaam stations, the frequency of severe wind speed events increased from 2013 to 2022 at a rate of 1.3/year whereas frequency of extreme rainfall events rose at a rate of 0.04 events/year and 0.3 events/year for Tanga and Dar es Salaam, respectively.

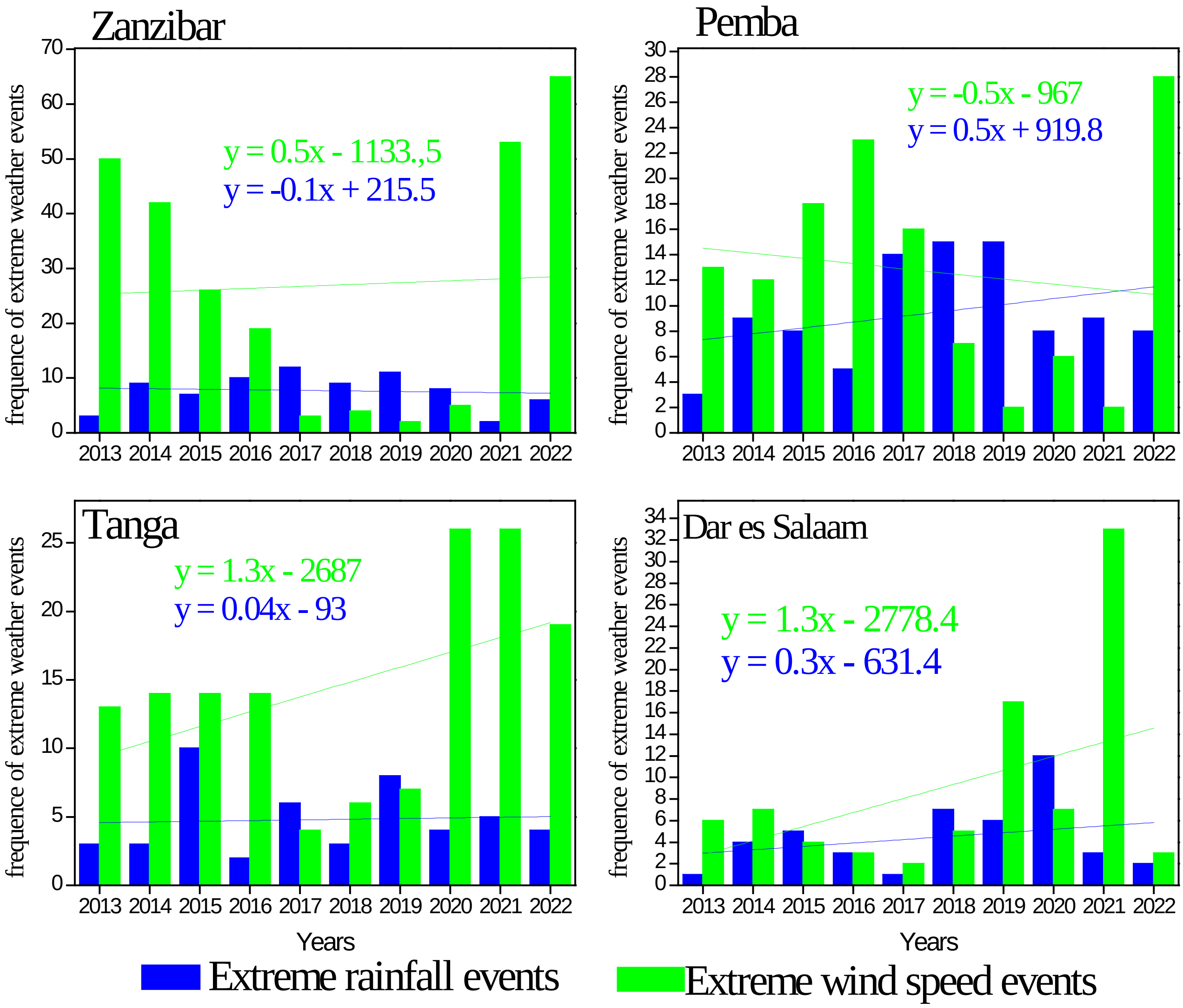


Figure 5. Annual distributions of extreme rainfall and wind events for Zanzibar, Pemba, and Tanga.

3.5. Mann-Kendall Test

Results of the Mann Kendall (Monotonic increasing and decreasing trend of frequencies of extreme rainfall and extreme wind) tests under confidence level of 95% (i.e., $\alpha = 0.05$) reveals that at Pemba there was a significant increase of the frequency of extreme rainfall events with a trend of $Z = 0.82$. Indeed, an increasing trend in extreme rainfall events was observed in Tanga, and Dar es Salaam with Z of 0.55 and 0.54, respectively, and decreasing trends of $Z = 0.27$ at Zanzibar. Moreover, frequencies of extreme wind strength events have shown a significant decreasing trend in Island stations of Pemba and Zanzibar with Z of −0.81 and −0.18, respectively, and increasing trend in Dar es Salaam and Tanga stations. The Sens slope estimated extreme wind speeds of −3, −1.43, 0.33 for Zanzibar, Pemba, Dar es Salaam and Tanga respectively, while for extreme rainfall events, the Sen's slope estimation was at −0.14 for Zanzibar, 0.5 for Pemba, 0.25 for Dar es Salaam and 0.125 for Tanga stations as presented in Table 1.

Table 1. Trends of the frequencies Extreme rainfall and Extreme wind speed events.

	Station	Z Score	S Statistics	Variance (var)	Sen slope	p-Value
Rainfall	Pemba	0.8238	10.0	119.333	0.5	0.41
	Tanga	0.5469	7.0	120.333	0.125	0.5844
	Dar es Salaam	0.541	7.0	123.000	0.25	0.5885
	Zanzibar	−0.2694	−4.0	124.000	−0.1428	0.7876
wind	Tanga	1.0939	13.0	120.333	1	0.274
	Dar es Salaam	0.44901	6.0	124.000	0.333	0.6534
	Pemba	−0.8082	−10.0	124.000	−1.4285	0.419
	Zanzibar	−0.1788	−3.0	125.000	−3	0.858

3.6. Accident Data Analysis

The analysis of the total reported accidents and their percentage contribution to the total accidents reported, reveals that accidents associated with bad weather conditions were 48 (32%) out of 150 reported cases. Other accidents included Unexplained cases (21%), Engine problems (20%), Fire (7%), Mechanical problem (3%), other causal factors including grounding, flooding, collision and overloading (13%) (**Figure 6**). As for the distributions of bad weather-related accidents, **Figure 11** shows that Nungwi area (northern tip of Unguja and southern Pemba) as well as Bagamoyo to Dar es Saalam areas are the hot spots for marine accidents (i.e. have higher number of weather-related accidents). Also **Figure 7** shows most of the accidents in the Pemba channel occur for vehicles navigating from Pemba and Mkokotoni to Tanga. The results indicate that many extreme wave events and worse ocean states occurred in Pemba channel rather than in Zanzibar channel.

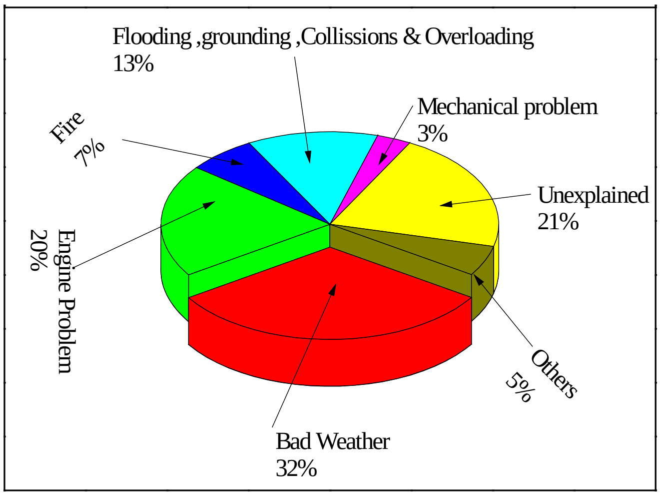


Figure 6. Distributions of marine accidents along Zanzibar and Pemba channels from 2009-2022.

3.7. Situations of Maritime Accidents

Results of the monthly records of the accidents caused by extreme weather events presented in **Figure 8** showed that the month of May is the period having a high frequency of accidents, it accounts for 10 (21%) out of 48 cases, followed by January 8 (17%) cases with July the third highest with 5 cases. Moreover, results showed that no accidents associated with extreme weather event were observed during November. In addition, Figure 9 shows the annual variability of the frequency of accidents associated with extreme weather events. Results have shown that accidents associated with severe weather have occurred at an increasing rate of 0.17/yr, while the years 2011, 2014 and 2021 were the worst ones by having 7, 6 and 8 accidents, respectively.

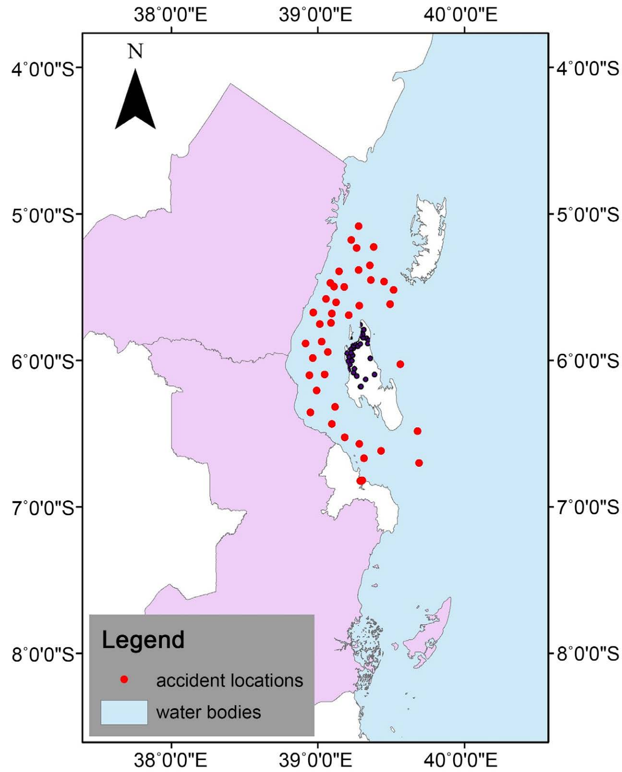


Figure 7. Distributions of the accidents caused by bad weather along Zanzibar and Pemba channels.

3.8. Relationship between Extreme Weather Events and Marine Accidents

3.8.1. Results from Interview

Results of the interviews and focus group discussions with the head of quays for the 8 quays of Mkokotoni, Malindi, Mazizini, Fumba, Nungwi, Nyamanzi, Bumbwini and Unguja Ukuu (all in Unguja) revealed that extreme weather events including strong wind and significant wave heights had dramatic impacts in causing marine accidents along Zanzibar and Pemba channels. For instance, during 2023, up to the month of May 15 marine accidents were reported at different quays of Unguja and Pemba channels (Figure 10(b)), of which 3 accidents for each quay were reported at Mkokotoni and Malindi, 2 accidents at each quay were reported at Mazizini, Nungwi and Fumba, while one accident per quay was reported at Nyamanzi and Bumbwini, respectively. As for the causes of these accidents, responses in Figure 10(a) show that out of 14 accidents reported, 6 (~43%) were caused by strong wind, 3 (~21%) were associated with strong wind and large waves, and two (14%) were due to strong wind and heavy rainfall, while technical faults e.g., overloading and Engine problem accounted for one (7%) of the total accidents. Moreover, respondents noted that many accidents incurred by the marine users including fishermen were associated with strong wind. Also, respondents noted that weak-geared vessels, including fishing boats and wind driven dhows, were highly affected by worsening ocean states due to severe wind and wave events. In addition, respondents revealed that the period from May to August was more dangerous for marine accidents due to the frequent occurrence of extreme southerly wind during the south easterly monsoon period. During this period the wind flow pushed the vessels away in northern parts of Zanzibar and Pemba Channels.

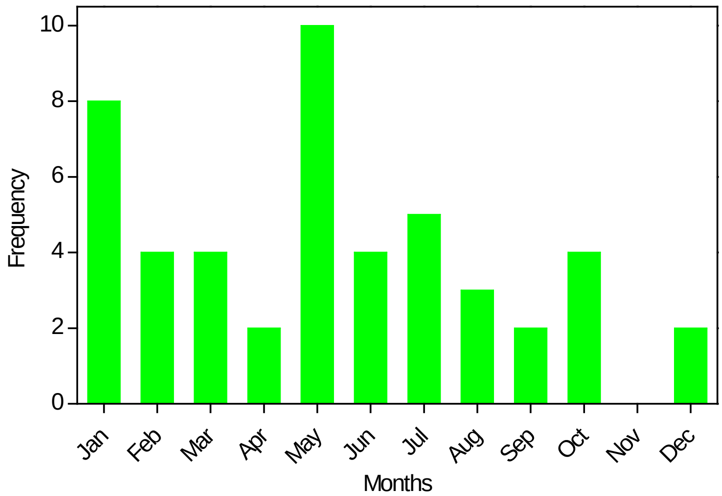
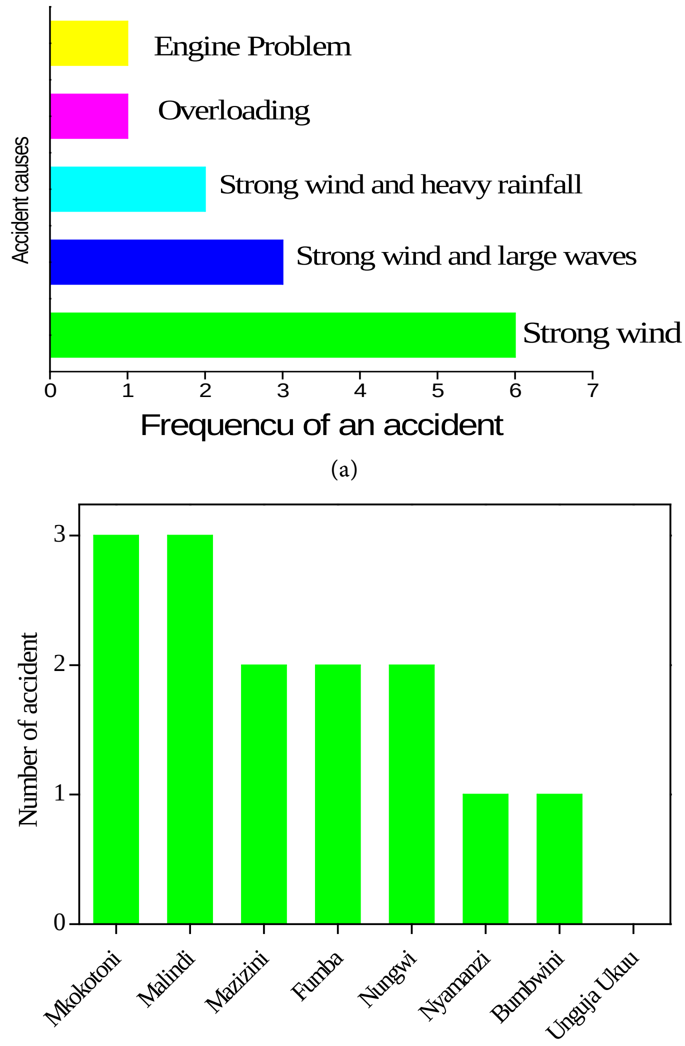


Figure 8. Monthly frequency of marine accidents associated with weather conditions along Zanzibar and Pemba Channels from 2009 to 2022.

Figure 9. Variability and trends of weather-related marine accidents along the Zanzibar and Pemba channels.



(b)

Figure 10. (a) Causes of accidents for all stations; (b) Number of accidents occurred in each landing site.

3.8.2. Relationship between Extreme Wind Events and Marine Accidents

The results of the Pearson correlation analysis for the frequencies of extreme weather events and number of reported accidents over the Zanzibar and Pemba channels yield a strong positive linear relationship between these two parameters (**Figure 11**). For instance, extreme wind speed events had a higher correlation with accident frequency with r = 0.73, ($p \leq 0.007$) and r = 0.71, ($p \leq 0.009$) at Tanga and Pemba, respectively. These results indicated that most weather-related accidents occurring along Pemba Channel have been associated with extreme wind strength, indicating that strong wind speeds are more significant in Pemba channel. Moreover, weak positive non-significant correlations were observed in Zanzibar (r = 0.17, $p \leq 0.596$) and Dar es Salaam (r = 0.29, $p \leq 0.367$), indicating that extreme wind strength was not a strong cause of marine accidents in Zanzibar channel (**Figure 11**).

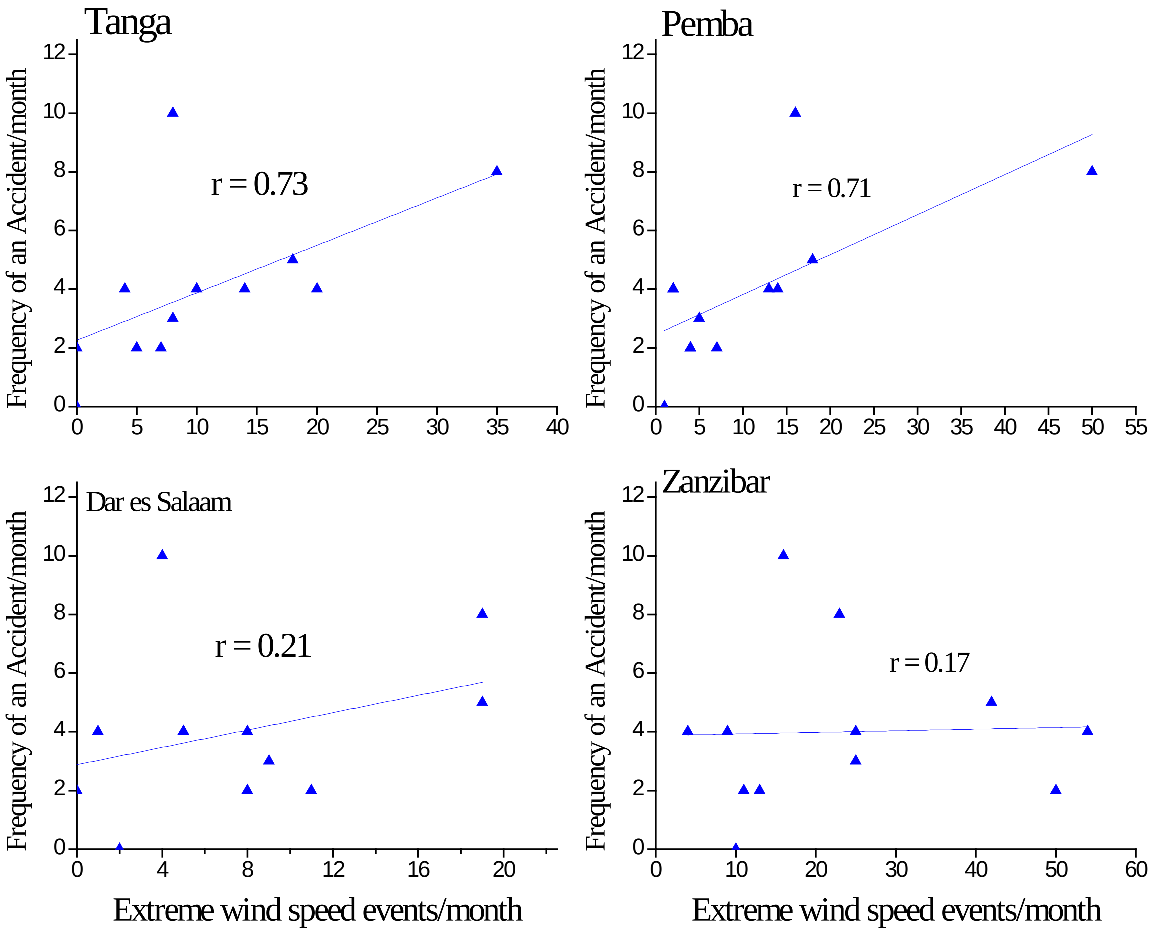


Figure 11. Correlation plot of frequencies of extreme wind speed and marine accident events.

3.8.3. Relationship between Extreme Rainfall Events and Marine Accidents

The results of the Pearson correlation analysis for the frequencies of Extreme rainfall events and number of reported accidents over the Zanzibar and Pemba channels yield positive linear relationship between frequencies for these parameters (Figure 12). The extreme rainfall events and marine accidents' correlation analysis resulted in a positive insignificant correlation of r = 0.55, and, r = 0.34, at Pemba and Zanzibar, respectively. These results indicate that though rainfall might reduce the visibility ranges for the Zanzibar channel, the occurrence of severe rainfall events have shown to be not critical events for occurrence of marine accidents, except when these events are associated with strong wind, such as the occurrence of thunder showers which are accompanied by thunderstorms and strong up and down drafts.

3.8.4. Relationship between Extreme Significant Wave Height Events and Marine Accidents

The results of the correlation analysis between the frequencies of extreme wave heights and marine accidents at $p \le 0.05$ presented in Figure 13 reveals a positive significant linear relationship with r = 0.41 (at $p \le 0.0006$) and r = 0.34 (at $p \le 0.006$) for Pemba and Zanzibar channels, respectively.

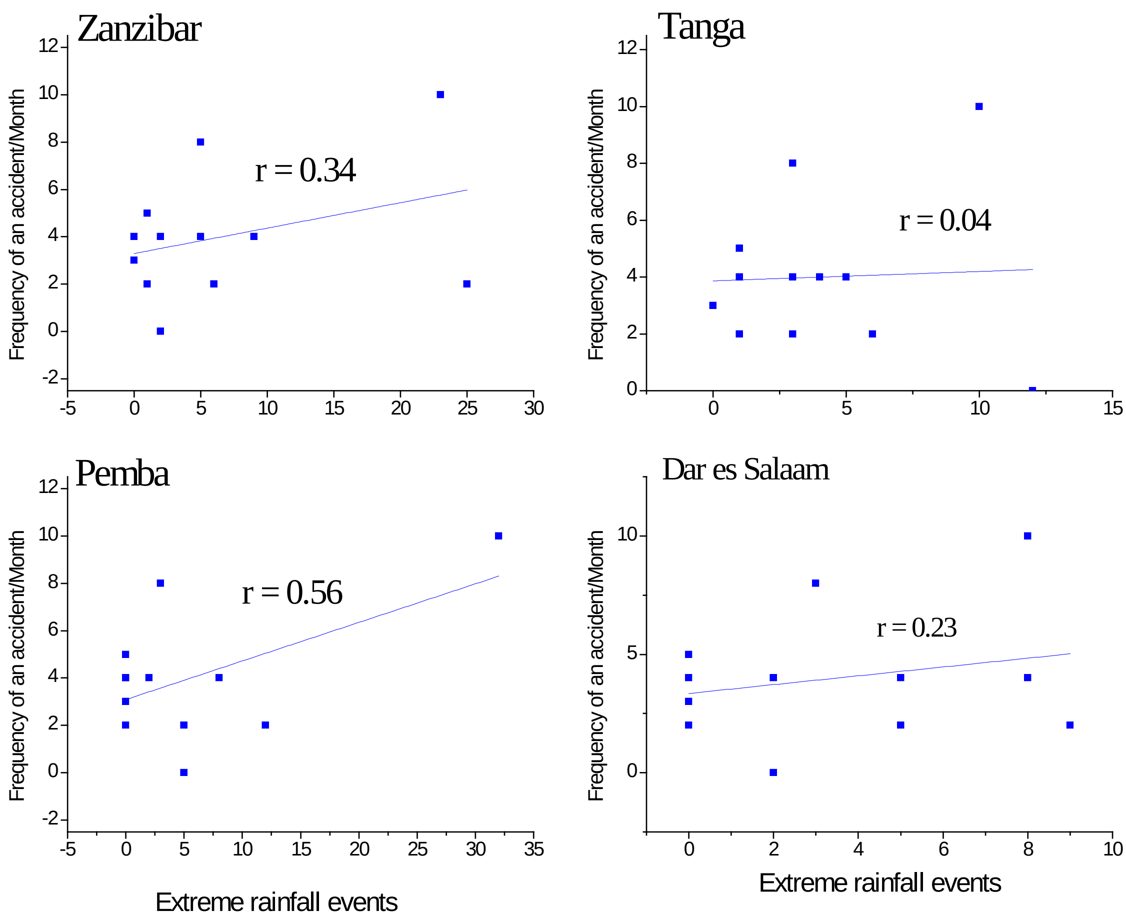


Figure 12. Correlation plot between extreme rainfall events and accidents events.

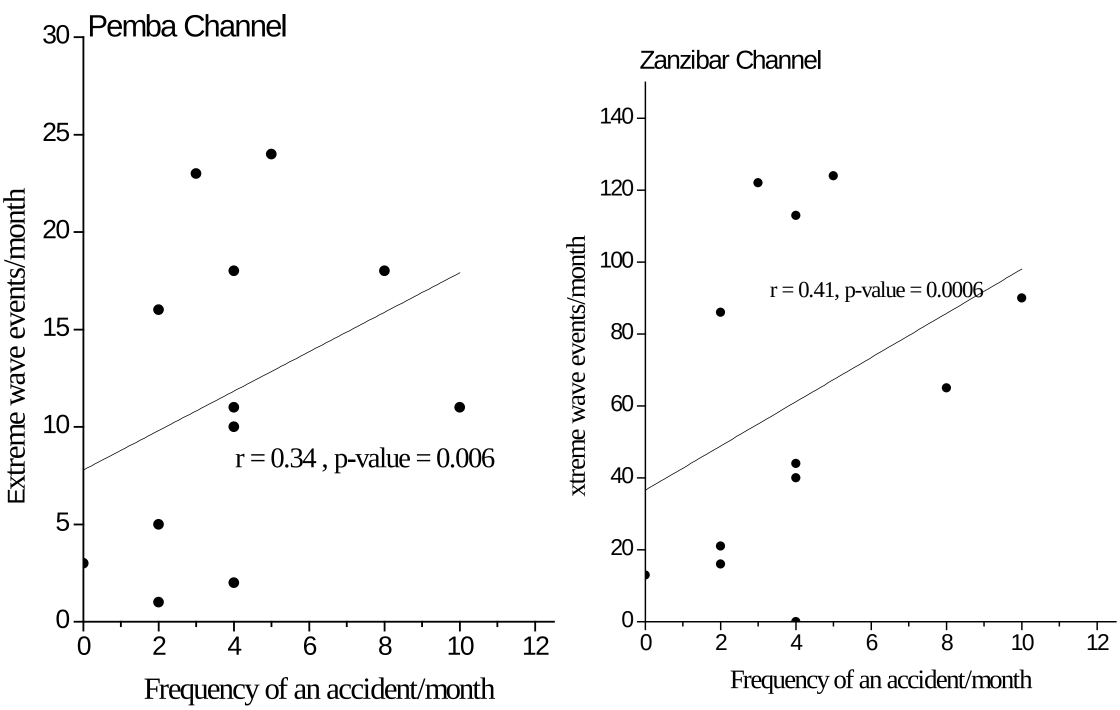


Figure 13. Correlation plot between extreme significant wave heights and marine accidents.

3.8.5. The Extent to Which Extreme Weather Influences the Marine Accidents

The extent to which the extreme weather events influence the marine accidents was evaluated using the paired t test (at $p \leq 0.05$) under the null hypothesis (Ho) that "there is no significant difference between the mean of these parameters for the two stated periods of 2013-2017 and 2018-2022". This hypothesis was rejected, and the alternative hypothesis (H1) that "there is significant difference between the means of both extreme weather events and marine accidents for the two stated periods" was accepted based on the results in Table 2, which indicated that the frequency of the extreme weather events are increased are the marine accidents for the two given periods are on increasing trends and taking on consideration that the two (marine accidents and climate parameters) are highly and significantly positive correlated, i.e. increase the intensity and frequency of extreme weather events results to more worse and frequent marine accidents, which are also increasing with time as the extreme weather events.

Table 2. Significance levels (p values) of extreme weather events and marine accidents for two periods at Zanzibar, Pemba, Tanga and Dar es Salaam at $p \leq 0.05$.

Parameters					
Stations	Rainfall	Accident	Wind	Extreme waves	
				P.Channel	Z.Channel
Zanzibar	0.7	0.6	0.9	0.7	0.6
Pemba	0.3	0.6	0.2	0.7	0.6
Dar es Salaam	0.1	0.6	0.1	0.7	0.6
Tanga	1.0	0.6	0.2	0.7	0.6

Note that Table 2 show that all the p values are greater than 0.05 indicating the rejection and acceptance of null and alternative hypothesis, respectively.

4. Discussions

The study has investigated the variability of extreme weather events (extreme wind, extreme wave heights and extreme rainfall) and their influences on marine accidents in Zanzibar and Pemba Channels. The extreme values of each parameter for the investigated stations of Zanzibar, Pemba, Dar es Salaam and Tanga were used in analysis. The presented results have shown that periods of extreme rainfall events were mostly observed in March, April and May (MAM period) for all stations with few period events in October, November and December. The presented results depict the rainfall characteristics of the study areas which fall in the bimodal regime rainfall of long rainy seasons (i.e. MAM and OND) as noted by (Hamisi, 2013) (Kai et al., 2021a) and (Chang'a et al., 2017). Also, the results have shown that the highest peaks of extreme rainfall events and accident events occur in Zanzibar and Pemba Islands, Moreover, the results presented have shown that the monthly variability of extreme wind events have their highest peaks in the months of June, July, to September as agreed by respondents from all quays. Also, the results have shown that respondents have agreed that the accidents caused by strong winds in JJA are accelerated by the occurrence of the South-easterly monsoon winds of June through September. Moreover, the results have shown that the hourly variability of extreme wind events mostly occurred during day time hours from 09:00 GMT to 15:00 GMT, as shown by (Mahongo et al., 2012). The results of the extreme significant wave heights are in correlation with the results of the extreme winds and not with the extreme rainfall events, indicating that whenever there exists strong wind events significant wave heights are also increasing in strength as supported by (Yun et al., 2020). Due to the presented high relationship between extreme wind speed and extreme significant wave height it could be concluded that in the Zanzibar and Pemba channels more marine accidents are incurred during strong wind episodes, which induces larges waves for the small marine vehicles to withstand.

Moreover, results presented from the trend analysis have shown that the frequencies of extreme rainfall events and extreme wind events was increasing from 2013 to 2022 at a rate 0.46, 0.31 and 0.04 for (Pemba, Dar es Salaam and Tanga) and 0.57, 1.33, 1.38, and −0.47 for (Zanzibar, Tanga, Dar es Salaam, and Pemba), respectively. This could be explained as a reasons for having higher % contributions (37%) of the accidents associated with the extreme weather events as compared to other causes of accidents, as highly supported by respondents from head of quay and dhow operators who daily navigate from one point to another in the Zanzibar and Pemba channels. Furthermore, the presented results of the variability of the accidents (**Figure 11**) have shown high accidents levels in May, July and January, which ties in with the variability and trends of extreme weather events in terms of their correlations and their patterns as shown in **Figure 11** and **Figure 12**.

5. Conclusion

By considering the stated specific objectives, research questions, analysis and detailed discussions, the study concludes the following:

1) Extreme weather events and marine accidents are highly variable in place and time and all are characterised by positive increasing trends over both channels and investigated stations.

2) Extreme weather events are highly and significantly correlated with marine accidents with extreme wind speed and wave height having higher correlation compared to rainfall for most stations.

3) Extreme wind and wave events are the leading causality of the marine accident events in the Zanzibar and Pemba channels and northern coastal Tanzania at large compared to rainfall events. For instance, Tanga, Pemba and Dar es Salaam have been shown to have higher frequency of extreme wind events compared to Zanzibar. These events normally worsen the ocean states by introducing strong waves.

6. Recommendations

In regard to detailed discussions of the results presented, findings and conclusions, the study recommends the following:

1) Since most of the presented results have shown strong impacts of wing and waves on marine accidents, thus responsible authorities including TMA, should ensure monitoring and routine forecasting of ocean sates and early warnings, and these forecasts are properly disseminated to all marine users through their respective organizations for undertaking their informed decisions.

2) ZMA, TASAC and other marine players should have to ensure that all marine vehicles (small and big ones) are obligated to undertake the weather and marine forecasts and early warning before departing to their harbour or their respective landing sites. Also the two should have ensured that accident events are well recorded for further use including research activities.

3) The ZMA, and TASAC should have ensured extensive capacity building in search and rescue rescue processes, and all marine vehicles are installed with GPS for enhancing the search and rescue activities.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

(2022). *Meeting Report for the Swiofc Nairobi Convention Partnership.*

(n.d.). *III Zanzibar Disaster Management Policy.*

Chang'a, L. B., Kijazi, A. L., Luhunga, P. M., Ng'ongolo, H. K., & Mtongor, H. I. (2017). Spatial and Temporal Analysis of Rainfall and Temperature Extreme Indices in Tanzania. *Atmospheric and Climate Sciences, 7,* 525-539. https://doi.org/10.4236/acs.2017.74038

Charter, A. (n.d.). *African Charter on Maritime Security and Safety and Development in Africa 1.*

Feidi, I. (2005). The Fisheries of Zanzibar: Potential for New Investments. *Food and Agriculture Organization of the United Nations, 28,* 37-40.

Hamisi, J. (2013). *Study of Rainfall Trends and Variability over Tanzania.* Ph.D. Thesis, University of Nairobi.

IPCC (2022). *Fact Sheets: Climate Change 2022: Impacts, Adaptation and Vulnerability.*

Jahn, M. (2015). Economics of Extreme Weather Events: Terminology and Regional Impact Models. *Weather and Climate Extremes, 10,* 29-39. https://doi.org/10.1016/j.wace.2015.08.005

Jiddawi, N. S., Stanley, R. D., & Kronlund, A. R. (2002). Estimating Fishery Statistics in the Artisanal Fishery of Zanzibar, Tanzania: How Big a Sample Size is Required? *Western Indian Ocean Journal of Marine Science, 1,* 19-33.

Kai, K. H., Kijazi, A. L., Osima, S. E., Mtongori, H. I., Makame, M. O., Bakari, H. J. et al. (2021a). Spatio-Temporal Assessment of the Performance of March to May 2020 Long Rains and Its Socio-Economic Implications in Northern Coast of Tanzania. *Atmos-*

pheric and Climate Sciences, 11, 767-796. https://doi.org/10.4236/acs.2021.114045

Kai, K. H., Osima, S. E., Ismail, M. H., Waniha, P., & Omar, H. A. (2021b). Assessment of the Impacts of Tropical Cyclones Idai to the Western Coastal Area and Hinterlands of the South Western Indian Ocean. *Atmospheric and Climate Sciences, 11,* 812-840. https://doi.org/10.4236/acs.2021.114047

Kai, K. H., Shaghude, Y. W., Kijazi, A. L., & Uiso, C. B. (2021c). The Influence of Tropical Cyclones to the Plant Productivity Indices along the Coast of Tanzania. *Atmospheric and Climate Sciences, 11,* 589-613. https://doi.org/10.4236/acs.2021.113036

Khamis, Z. A., Kalliola, R., & Käyhkö, N. (2017). Geographical Characterization of the Zanzibar Coastal Zone and Its Management Perspectives. *Ocean & Coastal Management, 149,* 116-134. https://doi.org/10.1016/j.ocecoaman.2017.10.003

Koesharyani, I., Gardenia, L., Widowati, Z., Khumaira, K., & Rustianti, D. (2018). *Indicators of Climate Change: Outcome of a Meeting Held at WMO 3 February 2017.* WMO.

Li, C., Jia, H., Wan, Y., Hu, Y., Zeng, B., Zhang, W. et al. (2023). The Impacts of Extreme Marine Weather and Marine Scientific and Technological Innovation on Marine Economic Development: Evidence Form China's Coastal Regions. *Frontiers in Marine Science, 10,* Article 1104045. https://doi.org/10.3389/fmars.2023.1104045

Luis, A. J. (2014). Trends and Interannual Variability of Winds and Turbulent Heat Flux in the Indian Ocean Sector of Southern Ocean during 2000-2009. *Atmospheric and Climate Sciences, 4,* 290-304. https://doi.org/10.4236/acs.2014.42030

Mahongo, S. B., Francis, J., & Osima, S. E. (2012). Wind Patterns of Coastal Tanzania : Their Variability and Trends. *Western Indian Ocean, 10,* 107-120.

McClanahan, T. (1988). Seasonality in East Africa's Coastal Waters. *Marine Ecology Progress Series, 44,* 191-199. https://doi.org/10.3354/meps044191

MLF (2020). *Ministry of Livestock and Fisheries Development: Commodity Value Chain Briefs.*

Msemo, H. E., Taylor, A. L., Birch, C. E., Dougill, A. J., Hartley, A., & Woodhams, B. J. (2021). What Do Weather Disasters Cost? An Analysis of Weather Impacts in Tanzania. *Frontiers in Climate, 3,* Article 567162. https://doi.org/10.3389/fclim.2021.567162

Nations, U., & On, C. (2009). *Multi-Year Expert Meeting on Transport and Trade Facilitation : Maritime Transport and the Climate Change Challenge.*

Peart, J., Tran, N., Chan, C. Y., Maskaeva, A., Shoko, A. P., & Kimirei, I. A. (2021). *A Review of Fish Supply—Demand in Tanzania: Penang, Malaysia.* World Fish.

Salby, M. L. (n.d.) Fundamentals of Atmospheric Physics.

Senthilnathan, S. (2019). Usefulness of Correlation Analysis. http://dx.doi.org/10.2139/ssrn.3416918

The Revolutionary Government of Zanzibar (RGoZ) (2020). *Zanzibar Blue Economy Policy.*

Wang, X., He, K., & Dong, Z. (2019). Effects of Climate Change and Human Activities on Runoff in the Beichuan River Basin in the Northeastern Tibetan Plateau, China. *Catena, 176,* 81-93. https://doi.org/10.1016/j.catena.2019.01.001

Watkiss, P., Bonjean, M., & Shaghude, Y. W. (2012). *The Economics of Climate Change in Zanzibar 1. Current Weather Data for Zanzibar and the Effects of Climate Variability and Extremes.*

Wilks, D. S. (2006). *Statistical Methods in the Atmospheric Sciences* (2nd Ed.). Academic Press.

Yun, Y., Xinxin, G., & Shengkang, Y. (2020). Study on the Relationship between Maritime Accidents and Bad Weather in Shanghai Coast. *IOP Conference Series: Earth and Environmental Science, 446,* Article ID: 052092. https://doi.org/10.1088/1755-1315/446/5/052092