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Sea Level Variability Assessment along the African Coast

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Abstract: Studying changes in the sea level is essential for the sustainable development of coastal areas. The aim of this study was to analyse time series and investigate the regional variability of the sea surface and the effect of individual factors on its behaviour. In this study, we utilised the most recent satellite altimetry data (over a period of 29 years, i.e., from 1993 to 2022) and tide gauge observations (long-term time series) in order to estimate changes in the sea level. Unlike in previous studies, the rates of the sea level changes around the entire African coast were determined. In addition, time series of the changes in the sea surface temperature and salinity were used to determine the rate of changes arising from the thermal expansion of the ocean. The regional rate of the sea level rise between 1993 and 2022 deviated significantly from the global average, with values ranging from 2.48 to 5.44 mm/year (based on satellite altimetry data, depending on the location of the point).

Keywords: African coast; sea level rise; satellite altimetry; sea water salinity; sea water temperature

1. Introduction

The rise in the sea level is directly caused by natural factors and human activities. The impact of individual components varies spatially due to ocean currents, land subsidence, and isostatic adjustment [1–3]. Currently, global warming is causing sea levels to rise in two main ways, namely, the thermal expansion of seawater and an increase in the amount of fresh water in oceans due to the melting of glaciers and ice caps. The rise in the sea level is seriously threatening coastal areas, especially local coastal and island ecosystems [4], as it causes irreversible economic losses, not only for agriculture but also other industry sectors. Some portions of the infrastructure in coastal zones and on islands are becoming increasingly damaged, thus disrupting the lives and safety of the inhabitants. Studying the sea surface along the coastline offers insight into the unique dynamics and factors contributing to coastline preservation in a given location. Such information is essential for land use planning, infrastructural development, and disaster risk reduction in vulnerable coastal areas.

Climate change is changing the ocean environment, leading to accelerated coastal erosion and changing the shape of the coastline [5]. Higher sea surface temperatures create a more significant gradient between continental thermal low-pressure and oceanic high-pressure systems, which enhances upwelling winds, causing regional cooling. Rising sea levels combined with increases in the frequency and intensity of storms are likely to have serious consequences for the economic infrastructure of oceans and coastal areas [6].

Coastal erosion is a natural phenomenon that affects coastlines. It consists of a coastline's movement towards land caused by the action of waves and ocean currents [7,8]. However, due to changes in various climates, atmospheric disturbances, and constant changes in water bodies, coastal erosion has become a global problem that affects virtually every country on the planet that has a coastline [7,9]. The consequences of climate change affecting coastal erosion are storm surges, monsoon patterns, wind–wave climate changes,

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and relative sea level rises, which will lead to increased rates of erosion, coastal compression, and more frequent and extreme storms [10–13]. The severity of erosion is directly proportional to the size of the wind and waves. Strong winds generate large waves and raise the level of sea water. Once formed, a wave approaches the shoreline and is transformed through processes such as refraction, diffraction, shoaling, and refraction [14,15]. A change in saltwater's temperature and salinity leads to a change in its volume [16] and thus to changes in the global mean sea level. In addition, the melting of the Antarctic and Greenland ice caps, climate change, changes in land-based water storage methods, and seawater evaporation result in geographically uneven differences in sea levels [17,18]. Land subsidence and tectonic plate movements are also factors that contribute to the establishment of the mean sea level on the global and regional scales [19–21]. Satellite altimetry observations indicate that the sea level is rising unevenly. In certain regions (e.g., the Western Pacific), it has been increasing three times faster than the global average level since 1993. Spatial patterns in sea level trends are mainly shaped by the varying warming of the oceans as well as changes in their salinity. Gravitational effects, as well as changes in the ocean circulation due to the continued melting of ice sheets and the inflow of freshwater, also have an influence. However, thermal expansion of the oceans is not a permanent feature, as it varies in space and time in response to natural disturbances of the climate system [22–25]. Many scientists analyse changes in the sea level and the factors contributing to these changes at different locations using altimetric, gravitational, and tide gauge data [26–28]. These changes can nevertheless be spatially variable [29,30]. Therefore, in order to calculate regional sea level changes, it is necessary to reject global average values and focus on local observational data. Africa is a continent located in several climatic zones, with the majority of its population settling near lakes and rivers and along the western and northern coasts. Since no comprehensive analysis of the entire coastline has been carried out to date, the current study examines the rate of sea level rises around Africa as a whole based on altimetric datasets (covering a 29-year period, from January 1993 to December 2022) and tide gauge datasets (constituting long-term time series). This study also takes into account changes in the water salinity and temperature.

The aim of this study is to address two key issues related to changes in sea levels. The first aim is to determine local changes in the sea level by calculating linear trends, while the second aim is to assess the effect of individual factors, namely, the water salinity, temperature, wind velocities, and ocean currents, on the values obtained through the determination of a correlation between them. The obtained results will enable the development of a more accurate and comprehensive system for assessing sea level changes along the entire African coast.

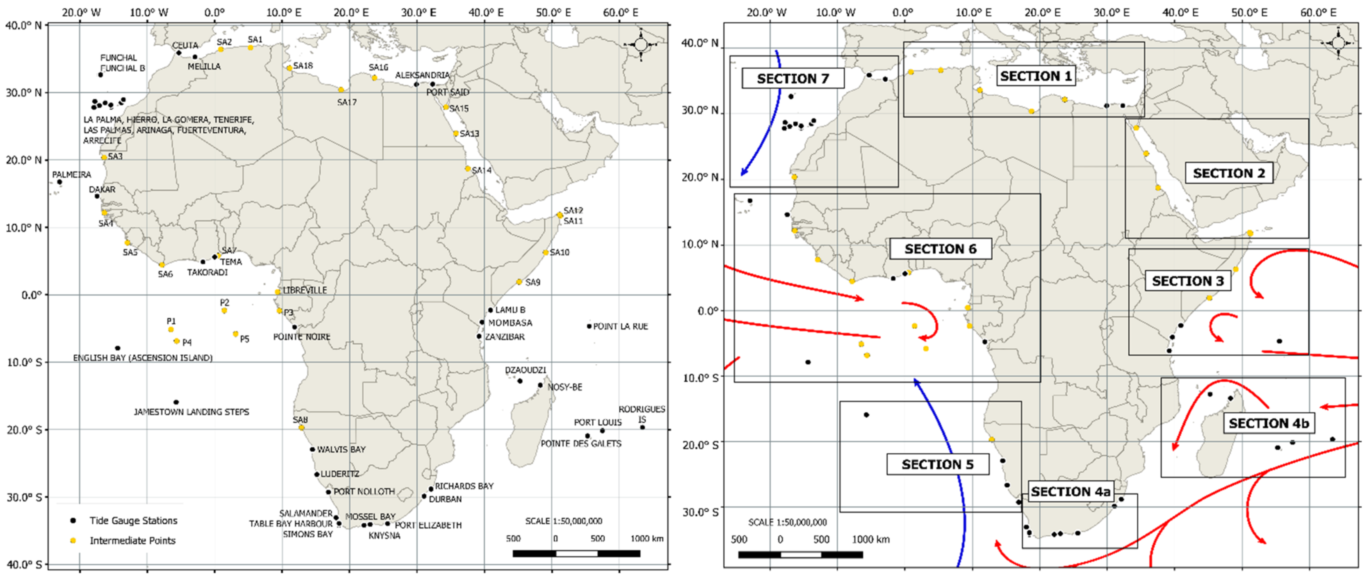
The 2030 Agenda for Sustainable Development (Transforming Our World: The 2030 Agenda for Sustainable Development) adopted by the United Nations (UN) is an action programme of unprecedented scope and importance, defining a model of sustainable development at the global level. The Agenda includes 17 goals for sustainable development and 169 goals that, seeking to be based on the development goals, including implementing human rights, are integrated and indivisible and balance the three dimensions of sustainable development: economic, social, and environmental. These goals will drive action over the next 15 years in areas of critical importance to humanity and the planet (Goal 13: Take urgent action to combat climate change and its effects; Goal 14: Protect and use oceans, seas, and marine resources sustainably) [31]. Our research fits into these goals because changes in the sea level caused by climate change seriously threaten coastal areas, especially local coastal and island ecosystems. These regions are most sensitive to the effects of extreme sea level rises. This increase precipitates irreversible economic losses not only in agriculture but also in other industries. Some infrastructure in coastal areas and islands is becoming increasingly damaged, disrupting the lives and safety of the residents. The study of the sea surface along the coastline allows us to understand the unique dynamics and factors contributing to the sea surface's behaviour in a selected location. Such information is essential for land use planning, infrastructure development, and disaster risk reduction in sensitive coastal areas.

This paper is structured as follows: Section 2—Study Area, Section 3—Materials and Methods, Section 4—Results and Validation, Section 5—Discussion, and Section 6—Conclusions.

2. Study Area

Africa is the world's second largest continent, and its coastline is approx. 30,000 km long. It is a continent located in several climatic zones, with the majority of its population settling near lakes and rivers and along the western and northern coasts. Over long distances, the African coast is uninterrupted by bays, and the main estuaries (with the exception of the Congo River) are either deltaic or bounded by sandy spits. The lack of convenient and secure harbours has, for a long time, challenged the development of the coastal area and its hinterland [32]. The African coastal zone consists of a narrow, low-lying coastal strip. It includes the continental shelf, the coasts of 32 countries, and a variety of ecosystems, such as barriers, lagoons, deltas, mountains, wetlands, groves, coral reefs, and shelf zones. These ecosystems vary in width from a few hundred metres (in the Red Sea area) to more than 100 km, especially in the Niger and Nile River deltas. In West Africa, the coastal zone encompasses a wide range of habitats, fauna, and flora, including on the islands of the Bijagos archipelago, the offshore islands of the Republic of Cabo Verde, São Tomé and Príncipe, and the remote islands of Saint Helena and Ascension in the mid-Atlantic. A large percentage of West Africa's urban population lives in coastal cities [33]. Nicholls and Cazenave [34] clearly indicate that the entire African coast is a region that is particularly vulnerable to coastal flooding due to the rise in sea levels. In recent decades, the sea level around South Africa has been rising at a rate of approx. 3 mm/year, which is in line with global estimates. Allison, Palmer, and Haigh [35] predict that by the year 2100, the sea level will rise by an average of 0.5–0.85 m in the South African region. These increases are about 7–14% greater than global projections for the average sea level.

Since no comprehensive analysis of the entire coastline has been carried out to date, the current study assesses the rate of the sea level rise around Africa as a whole based on satellite altimetry (SA) datasets (covering a 29-year period, from January 1993 to December 2022) and tide gauge (TG) datasets (constituting long-term time series). This study also takes into account changes in the water salinity and temperature. The study area comprises 47 tide gauge stations distributed unevenly along the African coast. Since the TG time series are not sufficiently precise (with short records, gaps, and jumps in the series), 24 intermediate points, for which altimetric observations are acquired, are included in the analysis. The study area is divided into seven sections, considering the location of the point and the direction and type of ocean current. Some points (13 stations in sections 6 and 7) are chosen from previous research [36]. The points' locations and their division into sections are shown in Figure 1.



(**a**) (**b**)

Figure 1. The locations of the stations (**a**) and the division into sections used to determine the sea level variability (**b**). Tide gauge stations are indicated by black dots, and intermediate points are indicated by yellow dots. The red arrows represent warm currents, and the blue arrows represent cold currents. Ocean currents source: available shapefile layer from ESRI company (Redlands, CA, USA) resources.

3. Materials and Methods

Materials were acquired from the following services:

1. Permanent Service for Mean Sea Level (PSMSL). This service provides time series of sea level measurements from tide gauges, reduced as Revised Local Reference (RLR) data, with each station having a different time span of data [37]. Data were accessed on 25 November 2021.
2. Copernicus Marine Environment Monitoring Service (CMEMS)—Global Ocean Gridded L4 Sea Surface Heights and Derived Variables Reprocessed 1993 Ongoing (Id: SEALEVEL_GLO_PHY_L4_MY_008_047). This service provides daily sea level anomalies, with a temporal extent of 1 January 1993–31 December 2021 and a spatial resolution of 0.25° × 0.25° (Level 4 gridded product) [38]. Data were accessed on 3 April 2022.
3. Copernicus Marine Environment Monitoring Service (CMEMS)—Global Ocea Ensemble Physics Reanalysis (Id: GLOBAL_REANALYSIS_PHY_001_031). This service provides monthly variables of the sea water salinity and sea water temperature, with a temporal extent of 1 January 1993–31 December 2021 and a spatial resolution of 0.25° × 0.25° (Level-4 gridded product) [38]. Data were accessed on 3 April 2022.
4. Copernicus Marine Environment Monitoring Service (CMEMS)—Multi Observation Global Ocean 3D Temperature Salinity Height Geostrophic Current and MLD (Id: MULTIOBS_GLO_PHY_TSUV_3D_MYNRT_015_012). This service provides monthly variables of the sea water salinity and sea water temperature, with a temporal extent of 1 January 1993–31 December 2022 and a spatial resolution of 0.25° × 0.25° (Level-4 gridded product) [38]. Data were accessed in 15 September 2023.
5. NOAA Physical Sciences Laboratory (NOAA PSL). This service provides the long-term mean monthly wind velocities (Gridded product: NCEP-NCAR Reanalysis 1—vwnd.mon.ltm.1991-2020.nc), with a spatial resolution of 2.50° × 2.50° [39]. Data were accessed on 18 December 2023.

This study involved an analysis of the rate of changes in the sea level and the rate of changes in the salinity and temperature at points distributed along the entire African coast. Initially, the positions of the intermediate points were determined to ensure uniform coverage and adequate density in relation to the tide gauge stations. The point coordinates were generated in the World Geodetic System 1984 (WGS 84). Real sea level anomaly (SLA) series were acquired from the CMEMS resources. The altimetric products were properly corrected and validated by the distributors to account for both atmospheric effects and geophysical processes. Information on the corrections is available via the industry portals in quality information documents (https://data.marine.copernicus.eu/products, accessed on 3 April 2022), (https://www.aviso.altimetry.fr/en/data/product-information.html, accessed on 3 April 2022).

Using multiple regression across the full range of the SLA data, additive models were created, and the linear trends of the sea level changes were generated. Time series devoid of a trend were used to analyse the periodic components. The seasonal cycles of sea level changes are not constant over time and result from the action of physical forces, i.e., atmospheric pressure, winds, and ocean currents. Therefore, precise estimation of temporal changes (amplitudes and phases) and the comprehension of physical mechanisms can be used to assess the effect of climate change on coastal ocean environments [40]. For this purpose, harmonic analysis was used, in which the aim is to use cyclic factors to reconstruct time series into the sine and cosine functions associated with a particular wavelength, yielding amplitudes in annual, semi-annual, and 18.61-year cycles (taking into account the Moon's nodal cycle). The 18.61-year cycle is a lunar nodal cycle caused by the Moon's relative motions. This important precession of the Moon, namely, the Moon's nodal cycle of 18.61 years, causes tidal modulations on several interannual time scales. These modulations affect the interpretation of data spanning several years, especially for extreme water levels [41]. Models of the sum of harmonics were created using the sine and cosine functions and by taking into account the lengths of the series. The amplitude values obtained result from the application of the following formula:

$$A_i = \sqrt{\left[\frac{2}{n}\sum_{i=1}^{n}\left(y_i sin\left(\frac{2\pi}{n}th\right)\right)\right]^2 + \left[\frac{2}{n}\sum_{i=1}^{n}\left(y_i cos\left(\frac{2\pi}{n}th\right)\right)\right]^2} \tag{1}$$

where A_i is the amplitude (annual, semi-annual, or 18.61-year), n is the length of the time series, y_i denotes a time series without the trend, t is the time, and h is the harmonics value ($n/365$ for annual amplitude, $2n/365$ for semi-annual amplitudes, and $n/6792.65$ for 18.61-year amplitudes should be adopted). The units are centimetres.

Based on the time series concerning changes in the salinity and temperature, the linear trends were determined, i.e., the trends of seawater salinity and seawater temperature. For the full time series ranges of the SLA data, the trends in the sea level changes were also determined using the assumptions of harmonic analysis, as shown in the formula below [41]:

$$f_h(t) = f(t) + \sum_{i=1}^{n=3} A_i \cos(\omega_i t - \varphi_i) \tag{2}$$

where $f_h(t)$ is a harmonic function; $f(t)$ is a trend function; t is the time; A_1, φ_1, and ω_1 are the in-sequence amplitude, phase, and angular frequency in the annual cycle; A_2, φ_2, and ω_2 are the in-sequence amplitude, phase, and angular frequency in the semi-annual cycle; and A_3, φ_3, and ω_3 are the in-sequence amplitude, phase, and angular frequency in the 18.61-year cycle. The units are millimetres per year.

A flow diagram of the study process is presented in Figure 2.

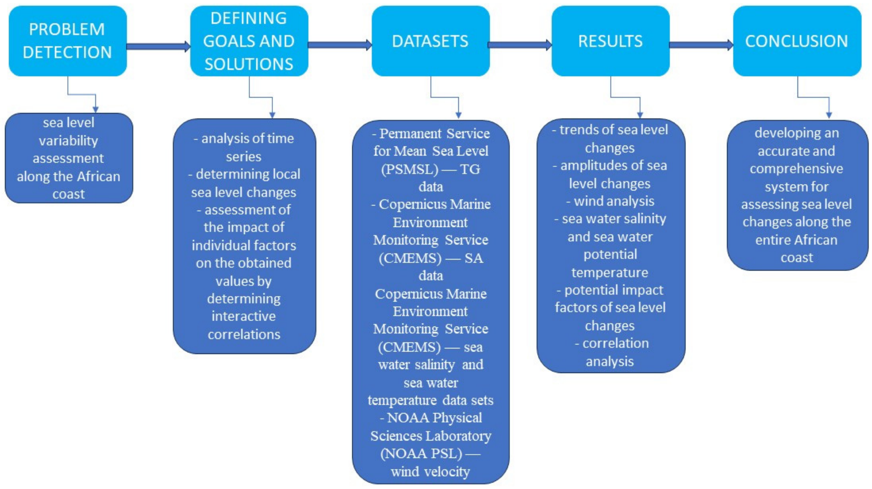


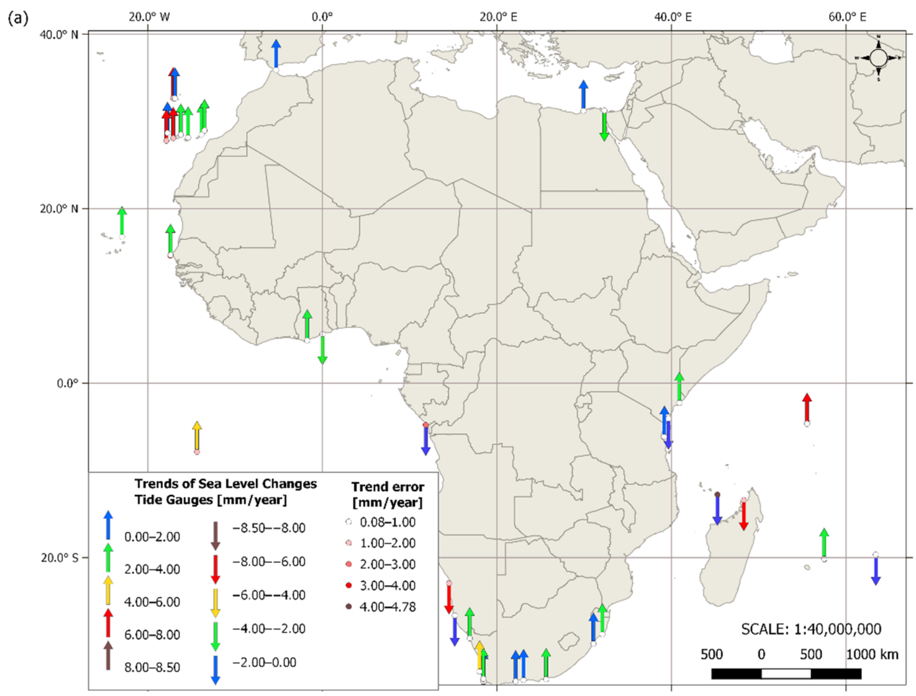
Figure 2. Flow diagram of the study process.

4. Results and Validation

The dynamics of the sea level changes along the entire African coast over a 29-year period (1993–2022) are highly variable due to their being largely dependent on the region analysed. The rates obtained were considerably affected by the wind velocities, the occurring ocean currents, and the water temperature and degree of salinity.

4.1. Trends of Sea Level Changes

The linear model employs the least squares method to calculate the trend line inclination. We employed the algorithm for fitting the linear regression via the least squares method to calculate the sea level changes, yielding the rate of the sea level change along the African coast from 1993 to 2022 (see Figure 3).



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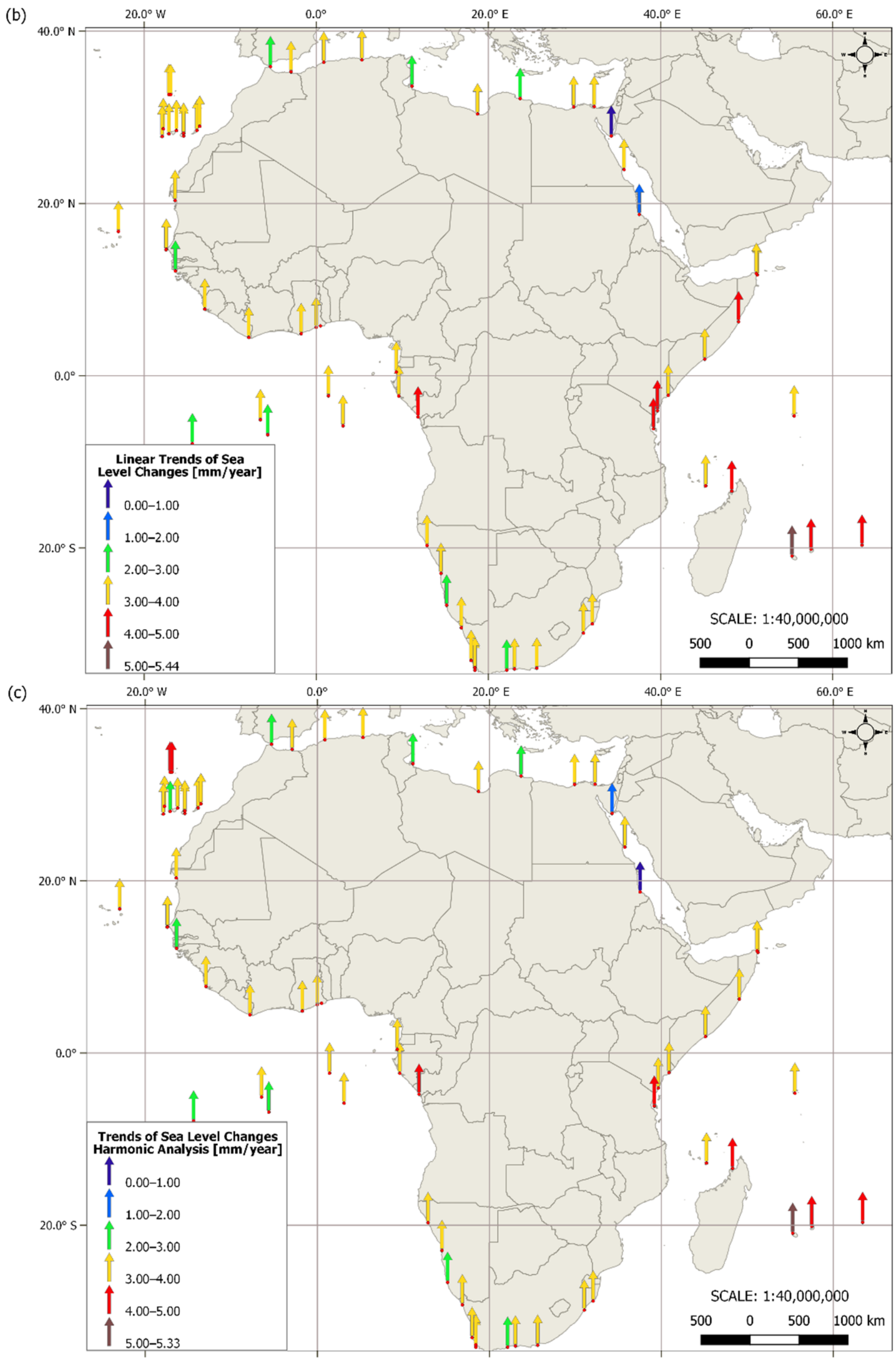


Figure 3. Linear trends of the sea level changes based on tide gauge data (**a**); trend values of the sea level changes based on satellite altimetry data (**b**); and trend values of the sea level changes determined via a harmonic function (**c**).

The trend values obtained based on TG time series data are highly variable, ranging from −8.50 to 7.64 mm/year. Moreover, they are affected by high errors (from 0.08 to 4.78 mm/year). Positive trend values can be observed in the north-western and southern parts of Africa. On the south-western coast, which is cooled by the Benguela Current, the trend values are negative. Large jumps in the values can be seen on the eastern coast. Tide gauges measure the relative sea level changes, taking into account the vertical land movement that is potentially important in coastal zones. They are also susceptible to the action of external factors, i.e., winds or erosion. The acquired time series were not sufficiently accurate (as there were large gaps and jumps in the series), which is why trend values are missing at individual stations. However, altimetric observations measure the geocentric sea level in relation to the Earth's mass and do not account for the contribution of vertical land movement. Their accuracy may be reduced near the coast, so the MSL rates from both the tide gauge and altimetry observations were used and compared [42–44]. For all the points, time series of the sea level anomalies were acquired from satellite altimetry (SA) data, and the sea level change trends (which were linear and determined using the harmonic function) were determined on their basis. In both cases, the trends fall within the up-to-5.5 mm/year range, with errors not exceeding 0.10 mm/year. Trends of less than 2 mm/year are evident in the Red Sea region. High trend values are found on the eastern coast, where only warm ocean currents are present. Based on the trend values, the coefficients of determination (R^2) indicating the degree of fit of the linear regression to the results for each tide gauge station are summarized in Table 1.

Table 1. Coefficients of determination for the TG stations (TG and SA measurements).

Section	TG Station	R^2 TG Data	R^2 SA Data	R^2 SA Data—Harmonic Analyses
Section 1	ALEXANDRIA	0.069	0.169	0.261
	PORT SAID	0.040	0.156	0.265
Section 3	LAMU B	0.225	0.318	0.705
	MOMBASA II	0.005	0.364	0.835
	ZANZIBAR	0.080	0.448	0.950
	POINT LA RUE	0.348	0.119	0.694
Section 4b	DZAOUDZI	0.001	0.136	0.746
	NOSY BE	0.190	0.370	0.822
	PORT LOUIS	0.026	0.219	0.637
	RODRIGUES IS	0.002	0.173	0.682
	POINTE DES GALETS	0.234	0.276	0.796
Section 4a	RICHARDS BAY	0.064	0.136	0.746
	DURBAN	0.015	0.120	0.784
	PORT ELIZABETH	0.310	0.154	0.566
	KNYSNA	0.018	0.184	0.510
	MOSSEL BAY	0.097	0.196	0.644
	SIMONS BAY	0.250	0.436	0.947
	TABLE BAY HARBOUR	0.383	0.413	0.923
	CAPE TOWN	0.259	0.413	0.922
	SALAMANDER	0.260	0.539	0.943
Section 5	PORT NOLLOTH	0.036	0.573	0.917
	LUDERITZ	0.141	0.489	0.788
	WALVIS BAY	0.218	0.516	0.811
Section 6	POINTE NOIRE	0.007	0.221	0.318
	JAMESTOWN LANDING STEPS	0.007	-	-
	TEMA	0.059	0.248	0.315
	TAKORADI	0.322	0.182	0.237
	ENGLISH BAY (ASCENSION ISLAND)	0.112	0.318	0.487
	DAKAR	0.049	0.162	0.188
	PALMEIRA	0.200	0.480	0.706

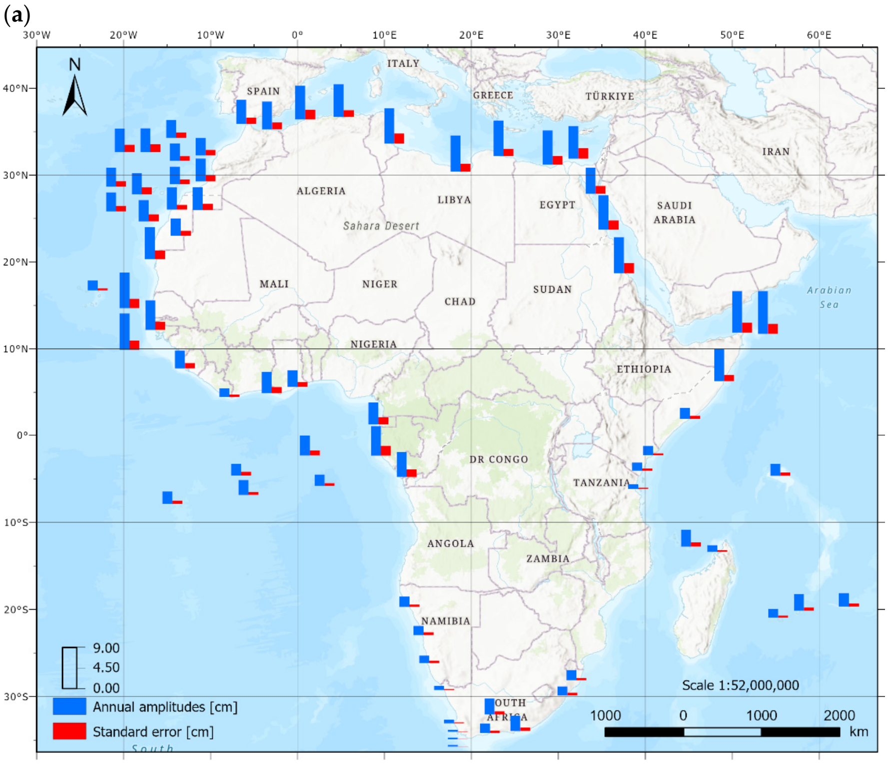
Table 1. *Cont.*

Section	TG Station	R^2 TG Data	R^2 SA Data	R^2 SA Data—Harmonic Analyses
Section 7	ARRECIFE	0.030	0.356	0.465
	FUERTEVENTURA	0.056	0.338	0.447
	ARINAGA	0.606	0.341	0.477
	LAS PALMAS	0.307	0.366	0.454
	TENERIFE	0.131	0.278	0.345
	LA GOMERA	0.150	0.245	0.343
	HIERRO	0.192	0.306	0.429
	LA PALMA	0.081	0.359	0.488
	FUNCHAL	0.055	0.319	0.433
	FUNCHAL B	0.113	0.316	0.443
	MELILLA	0.019	0.197	0.300
	CEUTA	0.191	0.137	0.206

4.2. Amplitudes of Sea Level Changes

Harmonic analysis is among the most commonly used methods for reconstructing time series using harmonic components of different frequencies for modelling the seasonal dynamics of the sea surface [45]. The time series acquired from satellite altimetry are affected by the seasonal signal; thus, the annual, semi-annual, and 18.61-year cycles were investigated using this analysis. In this study, we took into account the Moon's 18.61-year nodal cycle, which directly affects high tidal levels on a global scale. Models of the sum of harmonics were created using the sine and cosine functions, taking into account the lengths of the series. The distribution of the values of the annual, semi-annual, and 18.61-year amplitudes along the entire African coast is presented in Figure 4.

(a)



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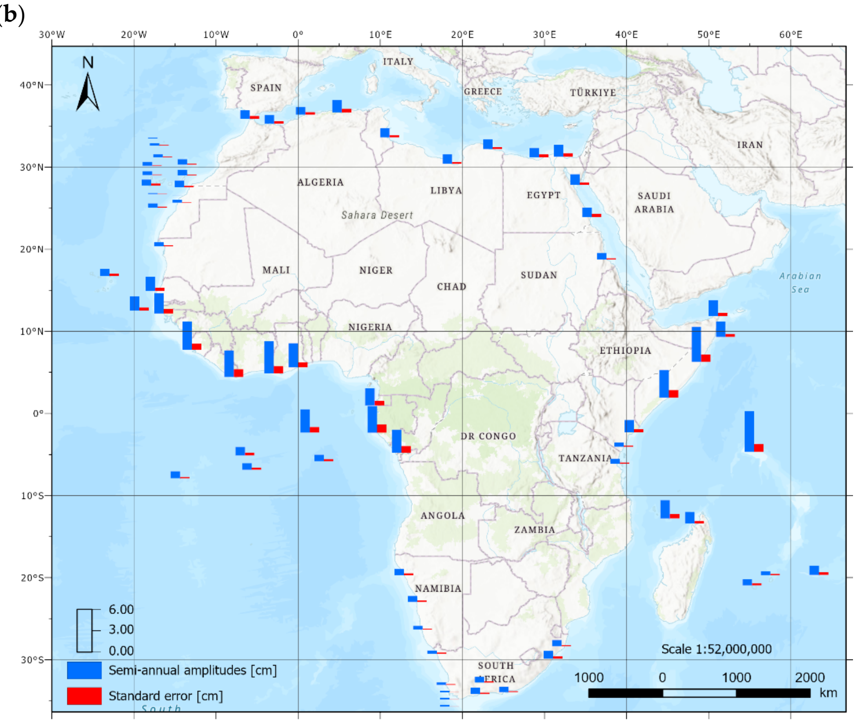
(**b**)



(**c**)

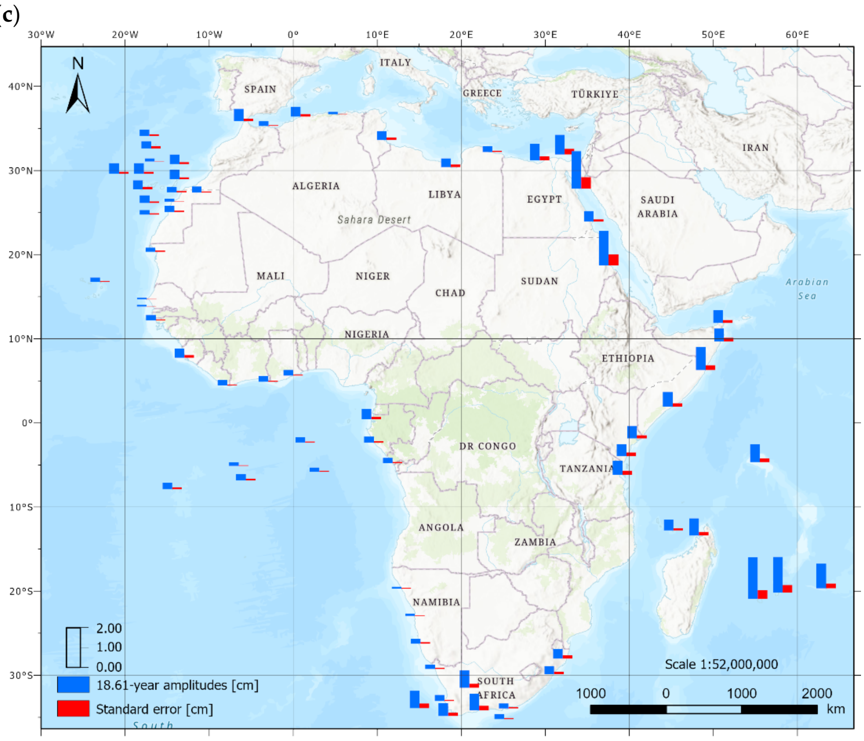
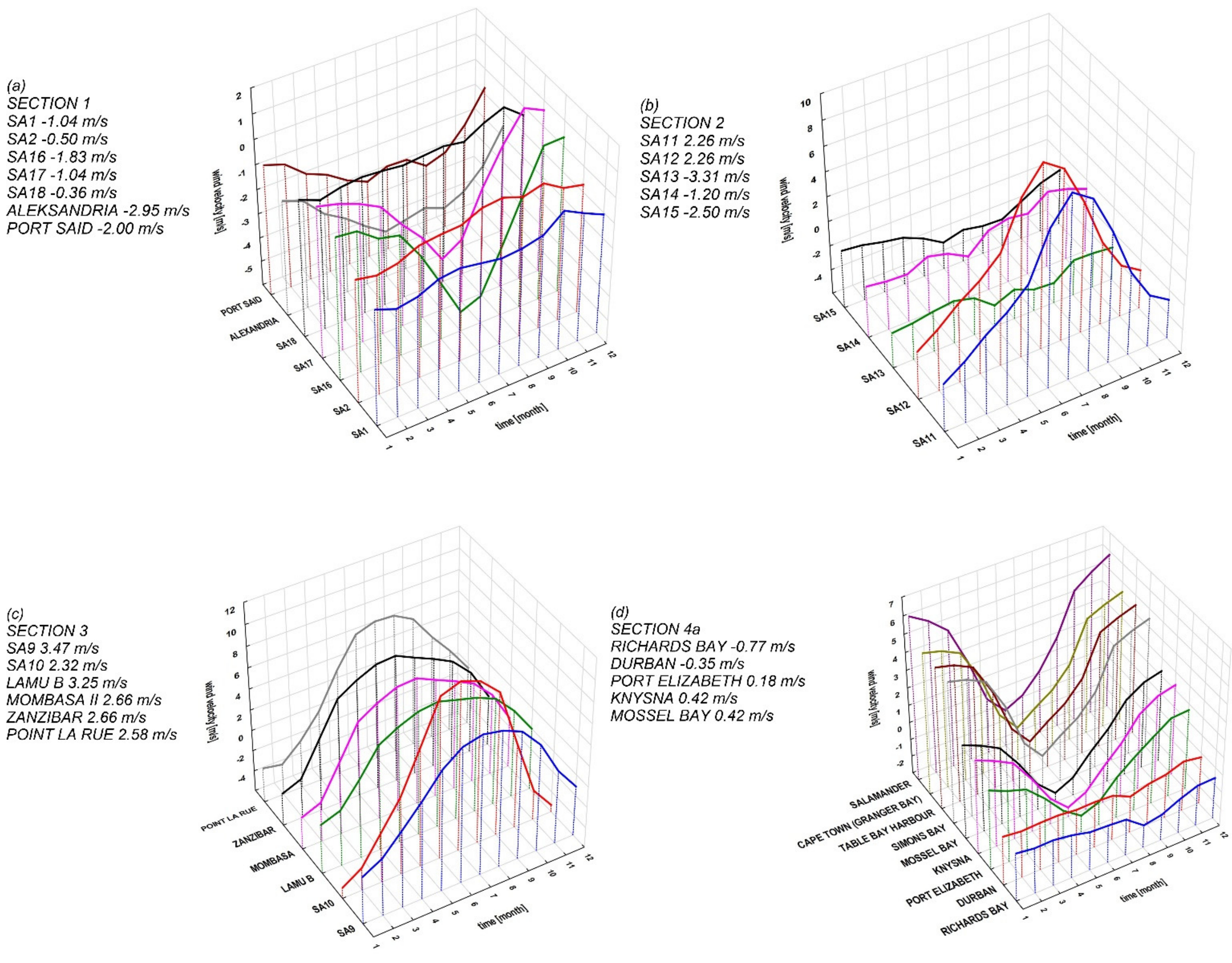


Figure 4. Amplitudes of the annual (**a**), semi-annual (**b**), and 18.61-year cycles (**c**). The units are centimetres.

Harmonic analysis was employed to estimate the annual, semi-annual, and 18.61-year cycles based on the SLA time series. The greatest variation is found at the inter-annual scales, while the least variation is found in the nodal cycles. The annual amplitudes take on the largest values in the northern and north-western parts of Africa (ranging from 3.00 cm to 9.00 cm). In turn, the smallest values are found in the south of the continent and in the Mozambique region. As regards the semi-annual amplitudes, a significant increase in the values can be observed in the equatorial region (rising from 3.00 cm to 6.00 cm). The 18.61-year amplitudes fall within a range of 1.00–2.00 cm and are greater on the eastern side of the coast.

4.3. Wind Analysis

The modelling of the sea level variability along the entire African coast includes an analysis of climatic factors that significantly influence extreme weather events. The examination of wind velocities in individual sections enables a local analysis of their impact on sea level extremes. Based on the long-term, averaged, monthly wind velocities made available by the NOAA Physical Sciences Laboratory [39], the linear trends of the wind velocities in particular sections between 1991 and 2020 are presented in Figure 5.



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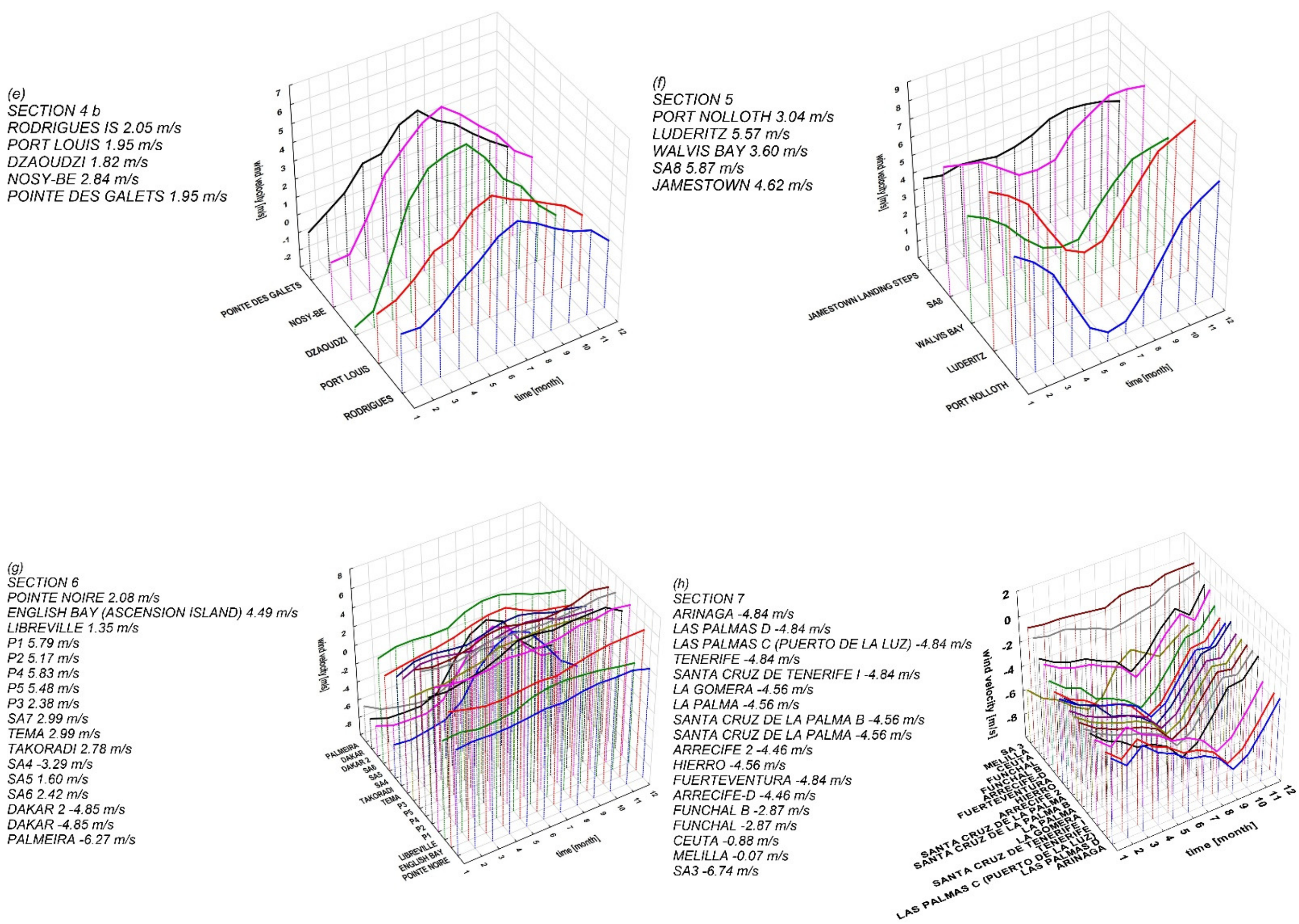


Figure 5. Mean wind velocities from 1991 to 2020 in each section.

The highest (as determined via linear and harmonic analysis) trend values are found in sections 3 and 4b. In the indicated sections, wind velocities maintain an increasing trend in the period from June to August, reaching over 5 ms^{-1}. At points SA11, SA12, DAKAR, DAKAR2, and SA4, at which the wind velocity trends increase rapidly in the summer, the trend values range from 2.00 mm/year to 4.00 mm/year. In sections 4a, 5, and 7, where the wind trends decrease during the summer period, the sea level change trends fall within a range of 2.00 mm/year–4.00 mm/year. At points SA15 and SA14, at which the trends are the smallest, the wind velocity is negative and amounts to approx. -2.00 ms^{-1}. It can therefore be concluded that higher sea level trend values can be found in areas where the wind velocities are higher. As demonstrated in a study by Lan, Kuo, Lin, and Kao [46], the wind force affecting the annual sea level cycle varies at different times and has a dominant influence on the coast. Since surface wind stress and heat flux are the main drivers of seasonal sea level changes at tropical latitudes, the correlation coefficients were determined to analyse the influence of the different sea level components between the resulting annual amplitudes and the wind velocities (see Table 2).

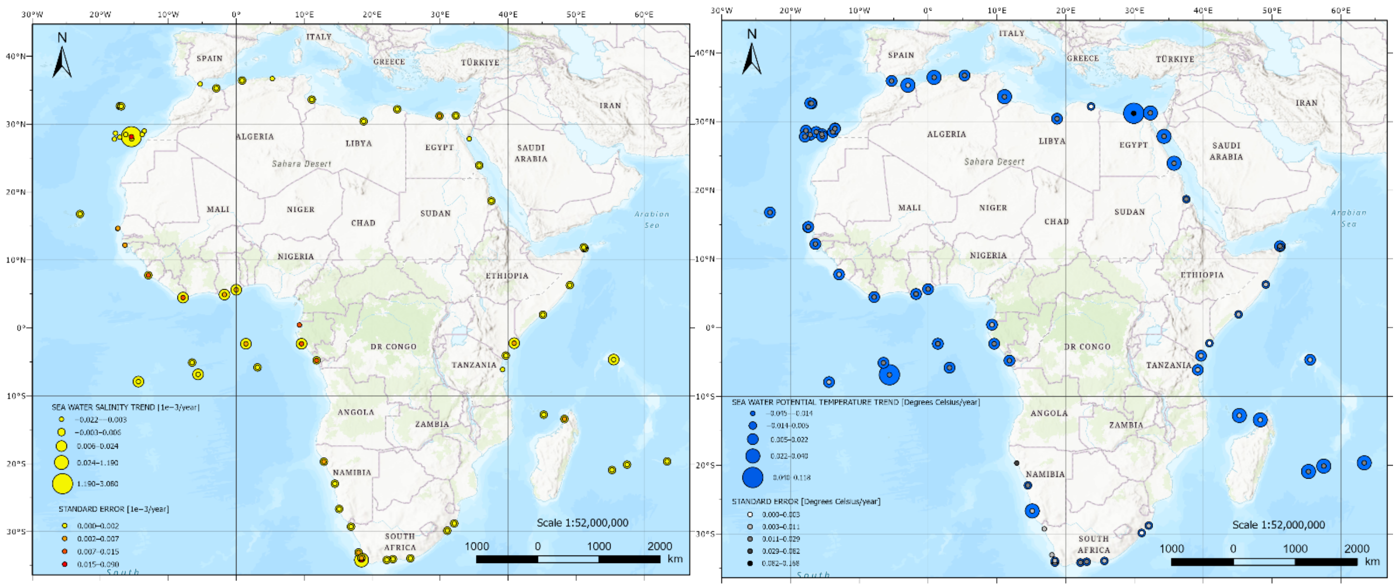
Table 2. Correlation coefficients between wind velocities and estimated amplitudes.

	Annual Amplitudes
Wind in Section 1	0.17
Wind in Section 2	0.83
Wind in Section 3	−0.46
Wind in Section 4a	−0.75
Wind in Section 4b	−0.80
Wind in Section 5	0.59
Wind in Section 6	−0.52
Wind in Section 7	0.21

As for the northern African coast (sections 1 and 7), periodic changes in the annual sea level amplitude show statistically low correlations with the wind velocities. The regional mean annual sea level amplitudes in the other sections are rather strongly correlated with the wind power (with coefficients above r = ±0.5). As for the semi-annual cycles and the 18.61-year amplitudes, the determination of a linear relationship is unnecessary due to the varying time scales.

4.4. Seawater Salinity and Seawater Potential Temperature

Fluctuations in the ocean temperature and salinity lead to global sea level changes, known as steric sea level changes. A steric change reflects the ocean's response to global warming [47–49]. As the seawater temperature and salinity fluctuations are small in deep waters (>200 m), we examined the dynamics of the changes in the salinity and temperature to a depth not exceeding 200 m (see Figure 6).



(**a**) (**b**)

Figure 6. Linear trends of the sea water salinity (**a**), and trend values of the sea water potential temperature (**b**).

The salinity change trend values along the entire African coast for most points fall within a range of up to ±0.020 1e−3/year. At individual stations, a few jumps occur: TEMA (0.024 ± 0.005 1e−3/year), LIBREVILLE (−0.022 ± 0.014 1e−3/year), SIMONS BAY

(1.19 ± 0.09 1e−3/year), and LAS PALMAS D (3.08 ± 0.05 1e−3/year). Negative values are predominant in the north-western part. In the Red Sea region, the salinity change trends are close to 0. The largest changes in the seawater temperature are observed in the Alexandria and Mozambique regions. Single jumps in the values can also be seen at stations P4 and LUDERITZ. The lowest values are evident in the south of the continent.

4.5. Potential Impact Factors for Sea Level Changes—Correlation Analysis

This study aimed at determining the dynamics of the sea level along the entire African coast and assessing the factors affecting this variability, i.e., the water salinity, temperature, wind velocities, and ocean currents. Therefore, following the identification of changes in the sea surface, the degree of correlation between individual components was estimated. A correlation analysis conducted using Pearson coefficients was employed (see Table 3). In addition, a comparative analysis of the trends obtained based on the SA and TG data was carried out (see Table 4). For the SA data, descriptive statistics were also determined (see Table 5).

Table 3. Correlation coefficients between estimated trends in each section.

Section	Sea Level Change Trend [mm/Year]	Wind Velocity [m/s]	Harmonic Function Trend, SA [mm/Year]	Salinity Trend [1e−3/year]	Temperature Trend [Degrees Celsius/Year]
1	SA trend Harmonic function trend (SA)	−0.75 −0.69	0.99	0.73 0.69	0.78 0.70
2	SA trend Harmonic function trend (SA)	0.46 0.31	0.98	0.72 0.59	−0.26 −0.06
3	SA trend Harmonic function trend (SA)	−0.38 −0.27	0.98	−0.66 −0.64	0.17 0.16
4a	SA trend Harmonic function trend (SA)	−0.23 0.18	0.66	−0.40 −0.78	0.49 0.71
4b	SA trend Harmonic function trend (SA)	0.10 0.01	0.91	−0.21 −0.11	−0.12 0.00
5	SA trend Harmonic function trend (SA)	−0.63 −0.83	0.93	0.65 0.75	−0.41 −0.49
6	SA trend Harmonic function trend (SA)	−0.20 −0.13	0.97	−0.12 −0.12	−0.24 −0.25
7	SA trend Harmonic function trend (SA)	−0.02 0.05	0.94	0.19 0.21	0.31 0.29

Table 4. Correlation coefficients and root mean square error of trends from TG and SA data.

Correlation/RMSE	Harmonic Function Trend (SA) [mm/Year]	TG Trend [mm/Year]	Salinity Trend [1e−3/year]	Temperature Trend [Degrees Celsius/Year]	Wind Velocity [m/s]
SA Trend [mm/year]	0.98/0.01	−0.18/0.32	−0.07/0.55	0.30/0.56	0.18/0.05
Harmonic Function Trend SA [mm/year]		−0.19/0.55	−0.10/0.54	0.37/0.31	0.13/0.60
TG Trend [mm/year]			−0.02/0.24	−0.03/0.24	−0.44/0.30

The relationship between the wind speed and an increased water level is not a universal correlation. In other words, an association for a specific area may not apply to other locations because each area has a different geographic location. For example, some shorelines may have a gentle beach slope, while others may have a steeper slope. Factors such as the location of the nearest wind and tide stations are important. The increase in the water level during high winds (Δ) is a function of the wind, waves, atmospheric pressure, and other factors. The main force that raises water levels is the wind. However, the waves that generate the wave-setting effect are produced by the wind. Differences in barometric pressure, referring to a barometric rise, also generate wind [10]. The highest correlations between the wind speed and the increased water level occurred in section 1 (with an average annual wind speed of 1.40 ms^{-1} and an average annual trend of sea level changes of 3.44 mm/year), i.e., the northern part of the African coast, and section 5 (with an average annual wind speed of 4.54 ms^{-1} and an average annual trend of sea level changes of 3.16 mm/year), i.e., the south-western part of the African coast. A high and consistent correlation was found in section 1 between the sea level change trend, salinity trend, and temperature trend. Sections 2 and 3 exhibit a high and consistent correlation between the sea level change trend and the salinity trend. A low-level and inconsistent correlation was found in sections 4a and 4b, as well as in sections 6 and 7.

Table 5. Descriptive statistics of the SA data for each section.

Section	Median SA Data/Standard Error	Kurtosis SA Data	Skewness SA Data	Variance SA Data
Section 1	3.56/0.08	−0.86	−0.52	0.15
Section 2	3.66/0.09	−2.80	−0.69	2.43
Section 3	4.02/0.06	−0.323	0.512	0.168
Section 4	3.48/0.08	−0.752	0.858	0.618
Section 5	3.11/0.03	−1.465	0.241	0.048
Section 6	3.46/0.07	−0.157	−0.258	0.142
Section 7	3.34/0.05	0.233	0.192	0.110

In this study, we found a low correlation between the sea level change trends calculated based on altimetric and tide gauge observations. The relationships are poor and inconsistent between locations. This may be due to the fact that we used two types of observational data that do not measure exactly the same changes in the sea level. They provide different and complementary information. TGs measure the relative sea level fluctuations, taking into account the vertical land movements that are potentially the most significant for coastal locations. When analysing the TG data, it can be concluded that these datasets are limited in terms of the size and quality. Altimetric observations measure the geocentric sea level in relation to the Earth's mass and take no account of the effects of the vertical land movement. No clear correlation is demonstrated between the TG time series and the wind velocity or salinity and temperature trends.

We analysed the altimetric observations, separately for each section, and the medians, which showed us that 50% of the data in the series have observation values no greater than 3.11–4.02, while the other half have observation values greater than 3.11–4.02, calculated as a positional measure. We also checked the kurtosis and skewness of the SA time series data. These measures provided information on how the variable values deviate when compared to the mean value. These, therefore, determine if the mean is found in the centre of the distribution (e.g., it is close to the median), how individual observations are dispersed around this mean, and the intensity of extreme observations. In sections 1, 2, and 6, negative skewness values are found; i.e., since one is dealing with time series with left skewness, most of the data in the series are larger than the mean. The greatest rightward skewness is found in section 4 and amounts to 0.858; i.e., a greater number of observations in the series are smaller than the mean. The kurtosis was also used to compare the distribution of the observations under analysis in the SA time series with a hypothetical normal distribution, in which the dispersion of observations around the mean is relatively uniform and there are no extreme outliers. In sections 1–6, it can be concluded that the intensity of extreme values is lower than that for a normal distribution. Only in section 7 are there series containing observations in which the intensity of the extreme values is greater than that in a normal distribution. In section 2, there are time series in which the observations exhibit greater intensity in terms of the extreme values than that in a normal distribution, with a kurtosis of

−2.80. The variances in the time series were also calculated in all the sections. In section 2, a great number of data values differ from each other. A high variance amounting to 2.43 was found; i.e., the observations are strongly dispersed around their mean value. Since the smallest variance is found in the altimetric observations in section 5 (amounting to only 0.048), the values of the SA observations in the series are close to each other, indicating a small scattering of the data.

5. Discussion

Determining the rate of sea level changes from tide gauge data and satellite elevation observations is an important way of sourcing information on the security and sustainability of African coastal zones. Africa's coasts are particularly sensitive to climate variability. Nevertheless, these are areas of intensive and diverse activities, such as artisanal fishing, firewood logging, charcoal production, sand mining, tourism, and industrial activities, including industrial processing and oil extraction. Such activities often lead to conflicts over resource exploitation, resulting in environmental degradation and potentially threatening the development potential of these areas [50]. Therefore, systematic scientific research in this area is necessary. Because 80–90% of the world's goods are transported by sea, the research results obtained in this field could have a positive impact on engineering issues related to the construction and operation of ports. Seaports are one of the infrastructures most threatened by climate change and, given their key role in global supply chains, adapting and protecting ports is crucial for global economic policy. The research conducted can also benefit the design of coastal fortification contraptions that prevent coastal erosion problems [51], provide protection from storm surges, increase access to beaches, and thus promote tourism [52]. Because of the points mentioned above, to avoid future economic and social losses and implement sustainable development strategies, it is important to study the impact of climate change on coastal areas and, based on the results, propose strategies and adaptation plans [53].

A study by Brown, Kebede, and Nicholls [54] noted that there is still limited knowledge of the potential consequences of rising sea levels for Africa on both the continental and local scales. The issue of rising sea levels along the African coast requires further attention and more detailed research. Research into sea level changes is usually mainly based on limited tide gauge measurements. Spatial and temporal gaps in African tide gauge recordings limit researchers' ability to monitor and understand the sea level observations as well as the drivers of sea level changes in the coastal zone. Satellite altimetry can help solve this problem by significantly increasing the spatial and temporal range of sea level observation systems [55]. The accuracy of altimetric measurements is higher in the open ocean but decreases in marginal seas and when approaching coastal areas [56–58]. Nevertheless, the use of these measurements to investigate changes in the sea level is necessary, as tide gauge observations are insufficient. Moreover, over the past decade, the potential of coastal altimetry has become increasingly attractive to coastal oceanographers [59]. There are studies in which the long-term variability of sea levels in selected areas of Africa has been determined based on different data at different time scales [60–67]. Some of these results can be compared with those obtained in this study. The trend values obtained based on TG time series data in this analysis are highly variable, ranging from −8.50 mm/year to 7.64 mm/year. What is more, they are affected by high errors (from 0.08 mm/year to 4.78 mm/year). Positive trend values can be observed in the north-western and southern parts of Africa. On the south-western coast, which is cooled by the Benguela Current, the trend values are negative. Large jumps in the values are found along the eastern coast of Africa. However, the TG datasets are limited in terms of the size and quality and cover several stations on a century scale at inter-tropical latitudes. Moreover, the stability of the ground on which the tide gauges are located is crucial in studying the rate of coastal sea level changes [68]. In the analysis, the altimetric measurements provided information on the change in sea levels along the African coast, with relatively small errors. The sea level change trends (linear and those determined using the harmonic function) were determined.

In both cases, the trends fall within a range of up to 5.5 mm/year, with errors not exceeding 0.10 mm/year. Trends of less than 2 mm/year are evident in the Red Sea region. High trend values are found on the eastern coast, where only warm ocean currents are present. The obtained results were compared with those from the existing literature and the SONEL Centre data (GNSS data assembly centre for the Global Sea Level Observing System) [69] (see Table 6).

Table 6. Results comparison.

TG STATION	Allison L.C. et al. [35]		Sonel [69]		In Work	
	SA [mm/yr]	TG [mm/yr]	SA [mm/yr]	TG [mm/yr]	SA [mm/yr]	TG [mm/yr]
PORT NOLLOTH	3.25 (1993–2018)	3.37 (1993–2018)			3.26 ± 0.01 (1993–2021)	2.11 ± 0.81 (2001–2015)
SIMONS BAY	3.05 (1993–2018)	4.63 (1993–2018)			3.18 ± 0.01 (1993–2021)	1.19 ± 0.08 (1958–2018)
MOSEL BAY	2.69 (1993–2018)	9.92 (1993–2018)			2.76 ± 0.02 (1993–2021)	0.80 ± 0.09 (1959–2018)
KNYSNA	2.59 (1993–2018)	2.97 (1993–2018)			3.12 ± 0.03 (1993–2021)	1.61 ± 0.99 (2007–2018)
PORT ELIZABETH	2.99 (1993–2018)	−0.21 (1993–2018)			3.48 ± 0.03 (1993–2021)	3.23 ± 0.23 (1982–2018)
DURBAN	3.83 (1993–2018)	3.87 (1993–2018)			3.47 ± 0.02 (1993–2021)	0.54 ± 0.18 (1971–2018)
RICHARDS BAY	3.48 (1993–2018)	2.75 (1993–2018)			3.29 ± 0.02 (1993–2021)	2.64 ± 0.67 (2000–2018)
ZANZIBAR			3.34 ± 0.35 (1993–2015)	3.61 ± 0.49 (1993–2012)	4.56 ± 0.01 (1993–2021)	1.49 ± 0.26 (1986–2016)
LAS PALMAS			3.36 ± 0.31 (1993–2015)	3.85 ± 0.33 (1993–2014)	3.08 ± 0.03 (1993–2021)	2.28 ± 0.15 (1975–2018)
DZAOUDZI			2.17 ± 0.70 (1993–2015)	3.82 ± 0.95 (1993–2012)	3.72 ± 0.04 (1993–2021)	−1.20 ± 4.78 (2009–2017)

A comparison of the obtained linear trends, calculated based on tide gauge and altimetry observations over similar periods, shows high consistency. The rate of the sea level rise in the years 1993–2018 (SA data), according to Allison et al. [35], ranged from 2.00 mm/year to 4.00 mm/year. The results of the authors' analyses and the SONEL Centre data are similar [69]. These values are comparable to the adopted global mean sea level rise. Based on the TG observations, the rate of the sea level rise is more varied. According to Allison et al. [35], at the Mossel Bay station, there are rather high jumps (9.92 mm/year), which may be associated with multi-decade changes of unknown origin taking place at this location. The authors suggest that perhaps the Mossel Bay station is more exposed to the impact of open waters or that this problem may arise from long-term quality control issues (perhaps related to reference instability). This study also obtained an outlier for the Mossel Bay station (0.80 mm/year) with a rather long time series, confirming the assumptions about the quality of recorders. The calculated Mean Sea Level Anomaly (MSLA) values from the SONEL Centre are similar for both the SA and TG trends [69]. According to Table 1, the authors noted that the best fit (highest coefficients of determination) to the regression model were the trend values determined via harmonic analysis (sections 4a, 4b, and 5, with a max. value of R^2 = 0.950). The lowest coefficient of determination (R^2) values corresponded to trends determined from the TG time series. The amplitudes determined using harmonic analysis reached quite high values: annual cycle amplitudes—max. value 9 cm, semi-annual cycle—max. value 6 cm, and 18.61-year cycle—max. value 2 cm. According to Wahl et al. [70], the seasonal cycle is a common signal of a sea level change and is subject to fluctuations under the influence of different physical forces, including atmospheric pressure, wind pressure, precipitation, river run-off, ice melting, oceanic currents, and the steric component [71]. An increase in the amplitude of the sea level's seasonal cycle during a storm season increases the risk of flooding and coastal erosion.

6. Conclusions

In this study, we aimed to carry out two crucial tasks: (1) determine local changes in sea levels by calculating the linear trends and (2) assess the effects of individual factors, namely, the water salinity, temperature, wind velocities, and ocean currents, on the values obtained by determining the correlations between them. The results obtained enabled the development of a system for assessing the sea level changes along the entire African coast. Over 29 years (1993–2022), the estimated trends showed interesting behaviours, depending on the region and section. For most cases, the trends (based on the SA data) fell within a range with a maximum of up to 5.5 mm/year, with errors not exceeding 0.10 mm/year. High trend values were found on the East African coast, and the highest (linear and Fourier) trend values were found on the southeast African coast. In the indicated sections, wind velocities increased from June to August, reaching over 5 ms^{-1}. Our analysis also showed a strong correlation between the annual amplitudes and the wind velocities. The salinity change trend values on the entire African coast for most points had an increasing tendency. Negative trends prevailed in the north-western part. The largest changes in the seawater temperature were observed in the northern and north-eastern parts of the African coast, while the smallest changes were seen in the south of the continent. The changes in sea level presented in this study revealed unexpected trends in the African coastal region, probably resulting from diverse processes taking place in the coastal zone. Since Africa is located in two hemispheres and the local conditions are variable, offshore winds can cause a significant increase in trends, and the influence of fresh river waters can alter the water density and affect the magnitude of the coastal sea level. Further research is needed to clarify the trends observed. In future studies, we intend to examine how coastal processes influence the upward trend noted along the African coast in areas located further offshore and the significance of sea-floor topography with respect to these trends. The coastal sea level dataset, compiled as part of this study, can provide valuable information for a variety of geospatial analyses.

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