Vertical Crustal Movement along the Coast of South Africa

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This conference paper is based on the authors' previously published article: Ghomsi F.E.K, Erkoç M.H., Raj R.P., et al. (2025). "Sea level trends along the South African coast from 1993 to 2022 using XTRACK altimetry, tide gauges, and GNSS measurements", Scientific Reports, 15:4946. https://doi.org/10.1038/s41598-025-89258-9. The paper summarizes key results of the published study for the ISPRS conference and is intended for dissemination within a broader geospatial science audience.

Keywords: Sea Level, Vertical Crustal Movement, Coastal Altimetry, Tide Gauge

Abstract

This study provides an in-depth evaluation of sea level rise (SLR) and its varied effects across the coastal regions of southern Africa. Utilizing data collected between 1993 and 2022, we analyze SLR patterns alongside land subsidence phenomena, based on observations from 10 strategically located tide gauges and X-TRACK satellite altimetry datasets. To ensure greater accuracy, the Coastal Altimetry Approach was adopted to refine nearshore measurements. Findings indicate that in areas such as Cape Town, sea-level rise rates reach around 6.3 mm/year, which is nearly twice the current global average of 3.3 mm/year. The interaction between rapid sea-level rise and subsidence rates surpassing 2.2 mm/year presents significant threats to coastal communities, critical infrastructure, and natural ecosystems. Moreover, the study highlights how seismic activity contributes to coastal dynamics, illustrating the role of earthquake-induced subsidence in magnifying the impacts of SLR. By incorporating seismic factors into the analysis, a more comprehensive understanding of the interplay between natural and human-induced drivers of sea-level variability is achieved. Additionally, the study examines the broader effects of SLR on Africa's culturally and historically important coastal heritage sites, emphasizing the urgent need for proactive coastal management and climate adaptation efforts.

1. Introduction

Sea level rise (SLR) is recognized as one of the most significant consequences of global climate change, posing substantial threats to coastal communities, particularly in the low-lying and vulnerable regions of southern Africa (Figure 1). Projections suggest that by 2035, nearly 143 million individuals will be living within 100 kilometers of the coastline in this part of the continent, markedly heightening their exposure to the adverse effects of sea-level rise (Maul & Duedall, 2019; Lockwood, 2020; Cazenave et al., 2022). As of 2021, Mozambique, Namibia, and South Africa had become the leading African nations in terms of the number of UNESCO World Heritage Sites, featuring three major coastal landmarks: the Namib Sand Sea, Robben Island, and Mozambique Island. These heritage sites not only draw millions of tourists annually but also serve as key elements of the region's cultural heritage and economic resilience (Gorenflo & Romaine, 2021; Vousdoukas et al., 2022). Safeguarding these ecologically and culturally important locations highlights the critical need to advance research on sea-level changes and better understand their future trajectories.

The region's exposure to the risks of sea-level rise is particularly severe in Mozambique and South Africa, where cultural heritage is increasingly threatened as the century progresses (Brooks et al., 2020; Vousdoukas et al., 2022; Nhantumbo et al., 2023). Shifts in sea level anomalies (SLAs) along the South African coastline are primarily attributed to changes in the dynamic topography of the Agulhas Current system, where intense baroclinic eddies play a dominant role (Nhantumbo et al., 2020). Given the concentration of human activities along the coastline and the region's dependence on marine resources, the repercussions of sea-level rise are not limited to environmental losses but also present serious economic and cultural vulnerabilities. Critical ecosystems and irreplaceable cultural landmarks across southern Africa are increasingly endangered by both advancing sea levels and the intensification of extreme weather events. Coastal monitoring studies have recently identified an average retreat of about 1.71 meters per year across 54 Blue Flag-certified beaches along South Africa's nearly 2800-kilometer-long coastline (Lucrezi et al., 2015; Murray et al., 2023). The severity of these changes is anticipated to increase as the century progresses, contingent on the trajectory of future climate scenarios (Abiodun et al., 2020; Raw et al., 2020; Allison et al., 2022). Globally, sea level rise continues at an estimated pace of 3.3 ± 0.3 mm per year, accompanied by a recorded acceleration of approximately 0.115 ± 0.01 mm per year² (Moreira et al., 2021; Guérou et al., 2023). Monitoring sea-level variations typically relies on two key measurement techniques: satellite altimetry and tide gauges (TGs). Both methods are instrumental in detecting regional sea-level patterns and understanding long-term trends, despite certain technical limitations. altimetry and tide gauges (TGs), both of which are crucial for tracking regional sea-level patterns. Nevertheless, TG records are subject to challenges such as sparse distribution, measurement errors, lack of uniform tidal datum, inapplicability to open ocean conditions, and susceptibility to vertical land motion (VLM). In Africa, evaluating regional sea-level trends is particularly difficult due to the limited network of TG stations. However, South Africa provides the continent's most comprehensive and consistent TG datasets, offering records that span over thirty years and cover both the Atlantic and Indian Ocean shorelines (Barroso et al., 2024; Nhantumbo et al., 2021; Allison et al., 2022). Although satellite altimetry has revolutionized large-scale ocean monitoring, its use in coastal zones remains complicated by limitations in resolution and data correction methods. This study undertakes a detailed analysis of sea-level changes along the South African coast between 1993 and 2022, utilizing an integrated framework that combines near-shore satellite altimetry and tide gauge observations. Relative sea-level trends are first evaluated using data from 10 coastal TG stations, while absolute trends are extracted from the X-TRACK coastal altimetry product. A central aim of this research is to reconcile the differences between TG-based and satellite-based sea-level estimates, enabling a more robust understanding of regional trends. By systematically addressing these inconsistencies and validating altimetry data against ground observations, this work advances local sea-level research and supports the development of informed climate adaptation strategies. Ultimately, the findings of this study contribute valuable knowledge to global initiatives aimed at mitigating the risks associated with rising sea levels. The findings presented in this paper have been previously published in Scientific Reports (Ghomsi et al., 2025). This version has been adapted for presentation at the ISPRS Congress to reach a broader geospatial research audience.

2. Method and Materials

2.1 Tide Gauge Data Analysis

Monthly mean tide TG data obtained from the Revised Local Reference (RLR) dataset of the Permanent Service for Mean Sea Level (PSMSL, http://www.psmsl.org), updated as of January 30, 2024, were examined for 10 stations located along the eastern and western coasts of South Africa, including Namibia, spanning the period from 1993 to 2023.
Tide gauges record relative sea level (RSL), which is subject to local influences such as vertical land motion (VLM). In this study, corrections for VLM and Glacial Isostatic Adjustment (GIA) were not applied, since the GIA effect (0.3 mm/yr) is consistent with the global average. Absolute sea level (ASL) estimates from satellite altimetry, inherently free from VLM effects, were compared with RSL measurements to calculate VLM based on the approach detailed in Eq. 1.

$$VLM = ASL - RSL \tag{1}$$

2.2 Coastal Altimetry Data

Satellite altimetry has become an indispensable tool for observing changes in oceanic sea levels. This approach utilizes radar altimeters to determine the separation between the satellite and the sea surface, referencing a standard ellipsoid model (Frederikse et al., 2021). The technique is critical for tracking variations in global sea levels and for analyzing broad-scale processes linked to climate dynamics. The formula used to compute satellite-based sea surface height (SSH) is given in Eq. 2 (Ghomsi et al., 2025).

$$SSH = Alt - S_{cor} \tag{2}$$

Table 1 Altimetry Data Sets.

Project	*Mission*	*Time*	*Type*
X-TRACK	T/P, Jason-1&2&3, Geosat Follow-on, Envisat, SARAL/AltiKa, HY2-A/B, CryoSat-2, Sentinel-3A&3B	1993-2022	Along-Track/Delayed

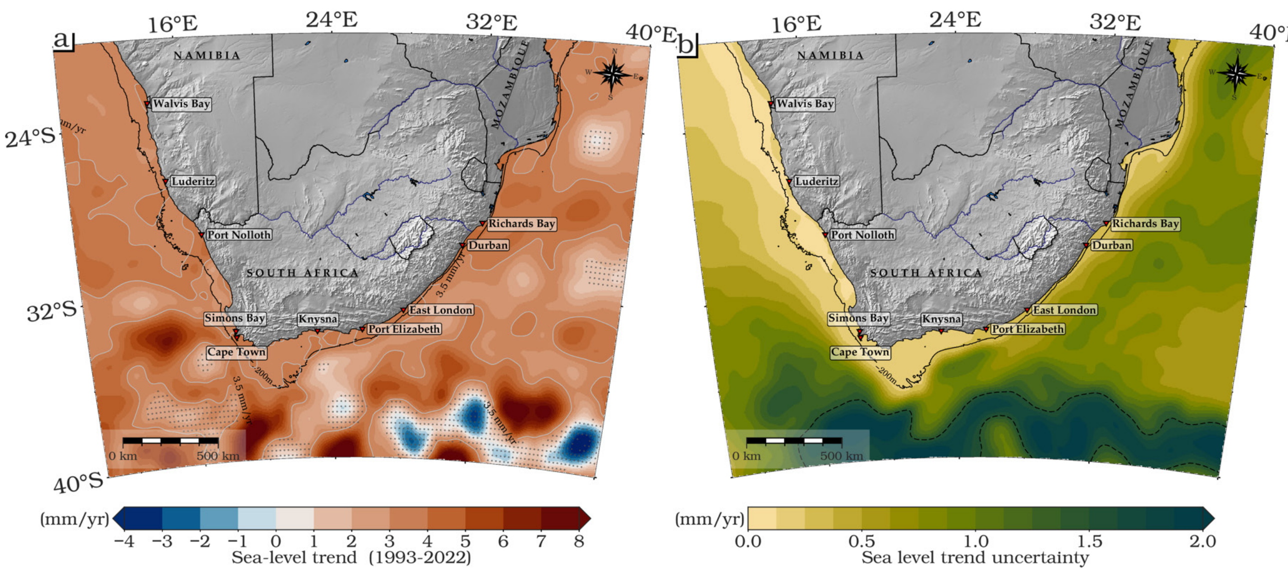

Figure 1 (a) Sea level trends (mm/yr) and (b) their associated uncertainty trends (mm/yr) at a 95% confidence level were determined using the Mann-Kendall test for the period 1993–2022. In Figure 1a, regions marked with black dotted patterns indicate areas where the observed sea level trends are not statistically significant at the 95% confidence threshold. In Figure 1b, dashed contour lines denote the areas where the uncertainty around the trend reaches 1.5 mm/yr. The 200-meter isobath is illustrated with a solid black line. (All figures were created using Generic Mapping Tools (GMT), Version 6.5.0, accessible at https://www.generic-mapping-tools.org/). Adapted from Ghomsi et al. (2025), Scientific Reports, under CC BY-NC-ND 4.0 license

In this context, SSH represents the instantaneous measurement of the ocean surface elevation, Alt indicates the height recorded by the satellite altimeter, and Scor corresponds to the corrected range, accounting for atmospheric and instrumental influences.
Based on the advantages outlined in previous research and elaborated upon within this section, the coastal altimetry approach was employed in this study.
The 1-Hz X-TRACK along-track sea level anomaly (SLA) datasets, labeled "SEA" and "WAFRICA," were obtained from the CTOH/LEGOS center (https://www.aviso.altimetry.fr/, accessed March 2024), encompassing data compiled from various satellite missions (refer to Table 1 for further details).

3. Results and discussion

3.1 Sea level trends over southern Africa from Altimetry

The spatial distribution of sea-level trends, illustrated in Figure 2a, reveals variations based on three decades of monthly mean altimetry observations. These trends range between approximately -4 mm/year and 8 mm/year, with positive trends most evident along the coastal regions, particularly over the Agulhas Bank (is a broad, shallow part of the southern African continental shelf, Figure 1), where rates of up to 2 mm/year have been recorded. This regional pattern aligns well with the global mean sea-level rise reported by Guérou et al. (2023) for the 1993–2021 period, marked by the 3.5 mm/year contour in Figure 1a.

In some localized areas, sea-level rise rates reach as high as 8 mm/year—exceeding more than twice the current global average of 3.3 ± 0.3 mm/year. Such rapid increases are cause for concern, as they surpass projected global rates and have the potential to intensify coastal hazards such as flooding, shoreline erosion, and habitat loss. Conversely, zones with negative trends of around -4 mm/year are mostly situated offshore within the Agulhas Return Current (ARC) system, rather than along the immediate coastline. These localized decreases in sea level are likely attributed to oceanographic processes including upwelling, dynamic changes in topography, and sediment redistribution, rather than to land-based factors.

The uncertainty map shown in Figure 1b highlights that trend variability generally ranges between 0 and 0.75 mm/year, indicating a high level of confidence in the observed patterns.
However, in the Agulhas retroflexion zone, uncertainties rise to around 1.5 mm/year, suggesting the presence of localized biases. Recognizing and accounting for such biases is critical for accurately interpreting long-term sea-level behavior in the study area.

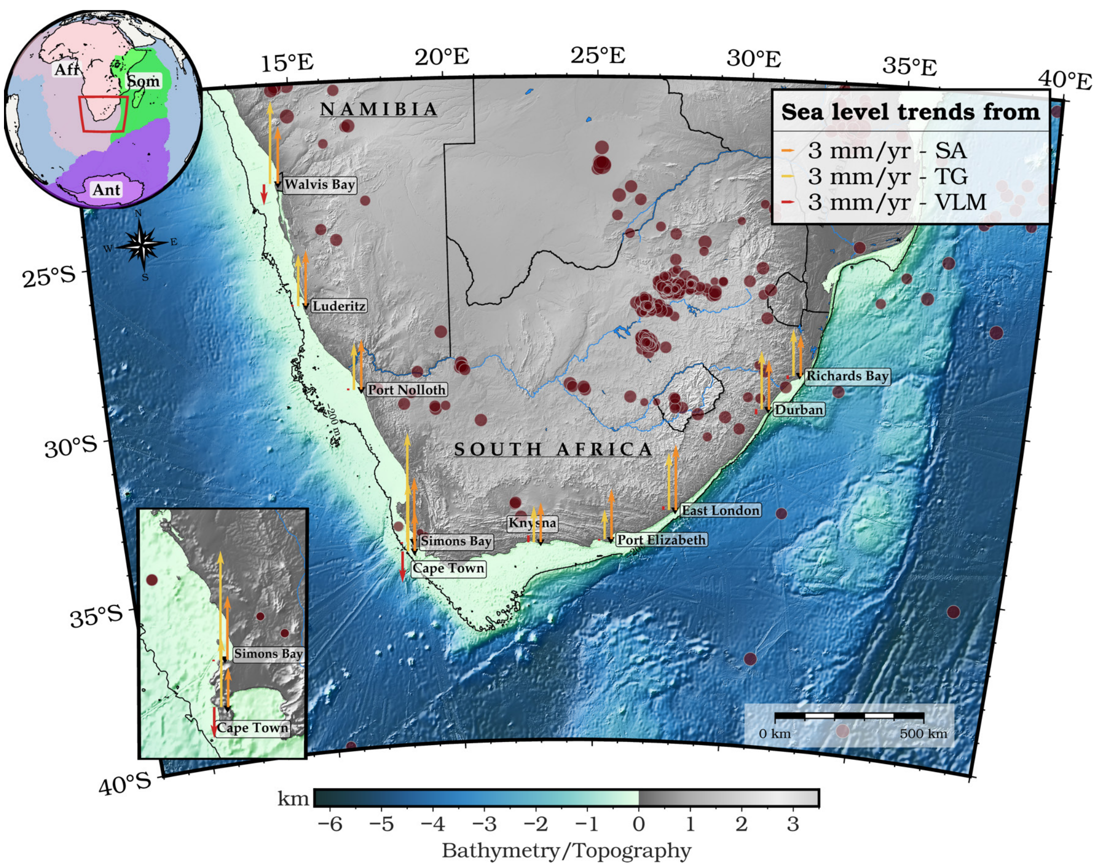

Figure 2 Sea level trends along the Southern African coast. Purple dots indicate earthquakes recorded between January 1, 1993, and December 31, 2023, based on data from the US Geological Survey. The inset highlights the most critical coastal stations, including Cape Town and Simons Bay. Adapted from Ghomsi et al. (2025), Scientific Reports, under CC BY-NC-ND 4.0 license

3.2 Comparison of Sea Level Trends and Vertical Land Motion Along the Southern African Coast

Figure 2 presents the observed trends in sea level along the southern African coastline, offering a detailed depiction of regional sea-level variations. One of the major contributing factors to these variations is land subsidence, particularly noticeable along the western coastline adjacent to the tropical Atlantic. Additionally, our analysis reveals that seismic-induced subsidence can amplify the effects of sea-level rise (Klos et al., 2019). This combined phenomenon is especially evident in locations such as Walvis Bay, Cape Town, Durban, and Richards Bay, where the interaction between subsidence and rising sea levels has led to localized sea-level elevations that exceed the global average.

Consequently, the region experiences seismic events less frequently than areas located along active plate boundaries. Nonetheless, intraplate stresses—arising from geological force transmission or the reactivation of pre-existing fault structures—can still provoke earthquakes.

According to the US Geological Survey (USGS, https://earthquake.usgs.gov/), 1,102 seismic events were documented across Southern Africa between January 1993 and December 2023. Significant seismic activity has been particularly recorded near Cape Town and along the coastal zone between Richards Bay and Durban. For instance, between September and November 2020, Cape Town experienced three consecutive earthquakes with magnitudes of 3.5, 2.6, and 2.7. Moreover, between 2019 and 2022, five additional notable earthquakes ranging in magnitude from 3.6 to 4.7 were observed in the Richards Bay–Durban region.

4. Conclusion

This study underlines the critical importance of addressing sea level rise (SLR) across the southern African coastline, where communities, ecosystems, and economies are becoming increasingly vulnerable. Our analysis reveals that Cape Town experiences a sea-level rise rate of approximately 6.3 ± 0.8 mm/year, with Walvis Bay, Simons Bay, and Durban recording rates of 4.8 ± 0.3 mm/year, 4.0 ± 0.2 mm/year, and 3.4 ± 0.4 mm/year, respectively—all surpassing global averages.

These changes are driven by a complex interplay of factors, including variations in ocean circulation patterns such as the Agulhas and Benguela currents, climate fluctuations, and localized influences like seismic-induced land subsidence, saltwater intrusion, and habitat loss. The impacts of accelerating sea levels—ranging from coastal inundation and erosion to freshwater contamination—demand immediate and targeted responses. Strategic measures such as adaptive urban development, integrated management of coastal zones, and infrastructure improvements are essential to safeguard regions at heightened risk. Furthermore, the presence of seismic activity, particularly in Cape Town and the corridor between Richards Bay and Durban, intensifies the effects of SLR by promoting land subsidence, thereby emphasizing the need for comprehensive risk assessments. This research deepens the understanding of the intricate dynamics of sea-level changes and their broader interconnections, supporting evidence-based decision-making and promoting sustainable coastal resilience strategies. Collaboration among scientists, policymakers, and stakeholders will be pivotal in developing effective solutions to protect coastal populations, conserve marine and terrestrial ecosystems, and ensure the sustainability of these regions for future generations.

Acknowledgements

F.E.K.G. receives funding from the Nansen Scientific Society through the Nansen-Tutu Centre Fellowship Programme. Additionally, F.E.K.G., R.P.R., and A.B. are supported by the Sea Level Predictions and Reconstructions (SeaPR) project, which is funded under the Bjerknes Center for Climate Research (BCCR) Strategic Projects Initiative. The authors also acknowledge support from the European Space Agency's DRAGON 5 project. Furthermore, this research has been funded by the National Research Foundation (NRF) of South Africa and the Canada 150 Research Chairs Program (Grant 50296). ChatGPT was used for English Editing. This conference paper is based on the following previously published article:

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