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The Impact of Climate Change on the Morphology of Marine Topography Using GNSS

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Abstract: In recent decades, very important scientific studies have focused on the effect of climate change on the average Sea Level Rise (SLR). Recent data has shown that 44% of the increase is due to the melting of glaciers and 42% to the thermal expansion of water due to the increase in average temperature. Research has focused mainly on the rate of Sea Level Rise from radar altimetry data (showing an average rise of 2.3 – 3.1 mm/year since 1970), or from coastal tide gauge data. In particular, although the coastal observations in closed seas agree with the data showing there is a trend towards an increase in sea levels, which is a result of climate change, they show significantly different rates of change. The question therefore arises: does climate change also affect the morphology of the Mean Sea Level (MSL) topography? In this paper, the research focuses for the first time not only on the change in MSL but also on the change in the morphology of the MSL topography. Research expeditions were carried out in the Gulf of Patras in 2011 and 2023. The method used is the new GNSS-on-boat method that, for the first time, makes it possible to examine the morphology of the MSL with an accuracy of up to 1 cm. The results show that in the area which was studied there was a significant change in mean sea level of the order of 2.78 cm in 12 years, which corresponds with the estimates of other researchers. However, what we observe for the first time is an obvious change in the shape of the sea surface. The significant changes in both the maxima and the slopes of the geoid exceed 8%.

Keywords: GNSS, Climate Change, Sea level rise, GNSS-on-boat, Environmental engineering

Introduction

The rate of Sea Level Rise (SLR) has never been constant. Geological research has shown that at the end of the last ice age (about 20,000 years ago) a rapid rise in ocean levels began, but it gradually slowed down and essentially stopped about 7,500 years ago (Leo et al., 2019). From this point until the industrial revolution the ocean level rose at a rate of less than 1mm/year (Griggs & Reguero, 2021). As is widely accepted, from the mid-19th century to the present, the widespread use of fossil fuels has doubled the amount of carbon dioxide in the atmosphere (from ~200 to ~400 ppm) and this has contributed to an increase in the average temperature of the planet by ~ 1.2 ºC (Lindsey & Dahlman, 2020; Lycourghiotis et al., 2017; Lycourghiotis, 2022). This increase has been reflected in rising ocean levels both due to the expansion of water and the melting of continental glaciers. According to the most recent report of the IPCC (Fox-Kemper, 2022) the global increase in the average sea level has reached a quarter of a meter (25 cm) from 1880 to the present day (figure 1). Bearing in mind that the phenomenon of SLR lags behind its cause, i.e. global warming, by many tens of times, it becomes clear that SLR will not stop for a long time, even if the rise in temperature were halted (Skea et al., 2022).

In recent years, research on the effects of SLR has focused mainly on the data provided by the Topex & Poseidon altimetry satellite missions since 1999, followed by the Jason-1, -2 and -3 satellites (Nerem & Hamlington, 2024). These missions give us an insight into SLR on a global level. The data show an average

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increase of nearly 11cm from 1999 to the present, with the rate of SLR increasing dramatically in recent years up to 4.8mm/year (Veng & Andersen, 2021). However, the influence of SLR is not the same in all parts of the planet. As tide gauge data show, the rate of increase in mean sea level varies significantly (Adebisi et al., 2021). Several local factors, such as tidal magnitude, ocean currents, and geological sedimentation can greatly influence the effects. Recent studies have shown that island regions near the equator, such as the Caribbean, the Philippines, Indonesia, etc. will experience multiple impacts from SLR within the next few years (Martyr-Koller et al., 2021)

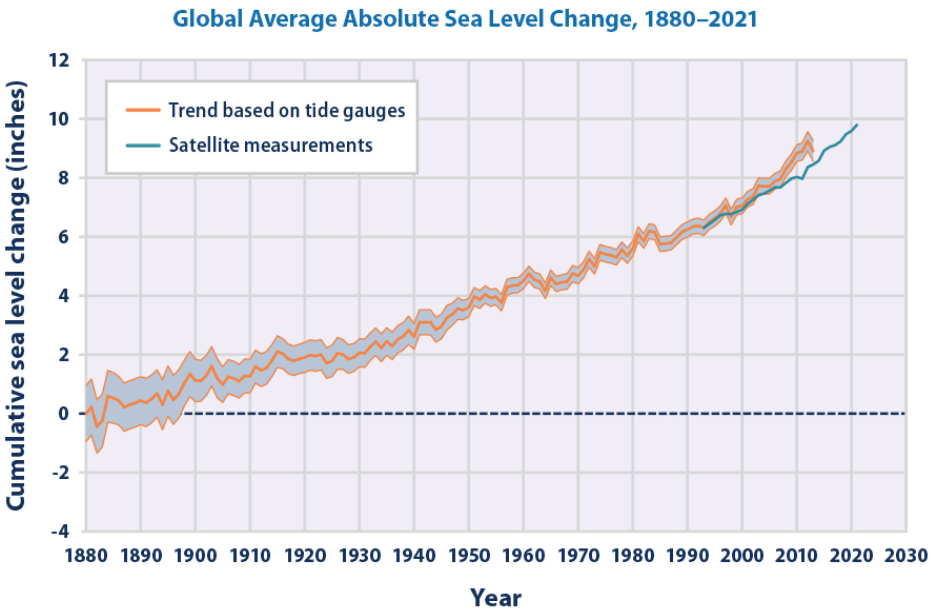

Figure 1. The global average sea level has rise since 1880 [Data source: Climate change indicators: sea level / absolute sea level change. EPA.gov. U.S. Environmental Protection Agency (EPA) (July 2022)]

Altimetry satellite measurements cover certain zones of the oceans (over the track of the satellites' orbit) while tide gauges measure only at specific and fixed coastal points and are not spread evenly over the planet. The limits and limitations of both methods make it imperative to add floating GNSS measurements to the study of SLR (Adebisi et al., 2021). In recent years a relatively new methodology has opened up a new field of research in the study of marine topography. This is the *GNSS-on-boat* technique (Lycourghiotis & Kariotou, 2022). This technique makes it possible to study the marine topography in coastal areas and closed seas where satellite and airborne methods usually fail, achieving an accuracy that reaches even 1cm (Lycourghiotis & Stiros, 2010; Lycourghiotis 2017a; 2017b; 2021). Although the GNSS-on-boat method succeeds in determining both mean sea level (MSL) and sea surface topography (SST) with very high accuracy, to date it has not been used to study climate change and in particular SLR. This is because the expeditions that have published data to date have focused their measurements on short periods of time, from a few days to a few weeks, and thus it is not possible to study the effect of SLR.

In this Paper, the GNSS-on-boat method is used for the first time in the study of climate change. Measurements made in the same area in two periods 12 years apart, in 2011 and 2023, are utilized. The area chosen was the Gulf of Patras (Greece), which is of great interest in terms of tectonic movements as it is an area which contains many active seismic faults (Ferentinos et al., 1985).

Significance of the Study Area in Light of SLR

The Gulf of Patras (Greece) is located between the Peloponnese and Western Greece (figure 2). To the west it is a natural extension of the Ionian Sea, from the island of Oxia to the cape of Araxos, while to the east it is bounded by the Rio-Antirion bridge. The bay has an area of 370 km² with a length of 40 to 50 km and a width of 10 to 20 km. Its deepest point (132m) is found approximately in the area of its geometric center. The gulf exhibits intense seismic activity while many active faults are present (Chronis et al., 1991). The city of Patras, the third largest city in Greece with a population of 200 thousand, lies on the south-eastern coast of the Gulf. The city is also a very important commercial port (Lycourghiotis, 2020; Lycourghiotis et al., 2021). The area is characterized by significant vertical geological movements. Several intense climatic events, such as the floods of January 1, 2010 (Lycourghiotis & Kontoni, 2012), April 18, 2012 (Lycourghiotis & Kontoni, 2014) and the most recent one (November 2017), which almost destroyed the city's marina (figure 2), have demonstrated the vulnerability of the region to climate change and specially to rising sea levels. Although the average astronomical tide in the area does not exceed 12cm (Lycourghiotis & Stiros, 2013; Lycourghiotis & Kontoni, 2012b), geological movements combined with extreme weather events make the need for a systematic study of the phenomenon imperative.

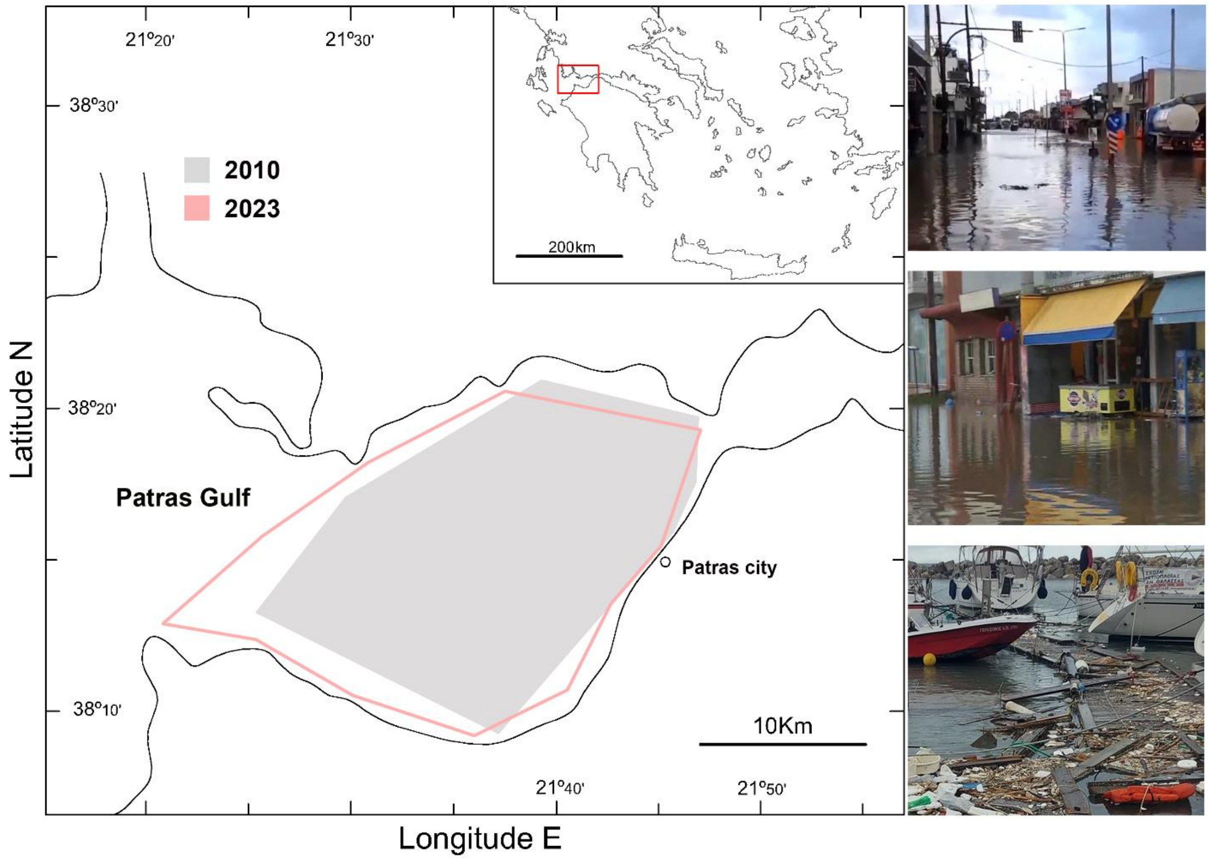

Figure 2. Location map of the study area and images of flood damages. The study area of the first mission (2010) is shown in grey, the of the second mission (2023) in red outline.

The Two Research Expeditions in the Study Area

Two research missions were carried out in the area of the Gulf of Patras, using the same GNSS-on-boat method. The first, in November 2010, employed a sailing vessel and a floating platform. The platform was of the catamaran type and carried 4 GNSS HiperPro receivers, which recorded at a rate of 1 Hz (Lycourghiotis, 2017a). The second expedition was carried out in the same area using a special research platform that carried 2 GNSS receivers and an accelerometer (Lycourghiotis & Kariotou, 2024). The sampling rate was 10 Hz. In both expeditions the central area of the Gulf of Patras was swept almost in its entirety. In the first mission, 3 days of data were collected, while in the second, data was recorded over a period of 7 days. In addition, tide prediction models, namely TASK, as well as tide gauge data in the port of Patras were used. The processing of data noise was affected using special software developed by us (Galani et al., 2021)

Methodology

The raw data of the first expedition was resolved using two methods, DGNSS and Precise Point Positioning (PPP) (Li et al., 2011). Figure 3 summarizes the overall methodology as presented in earlier work [16].

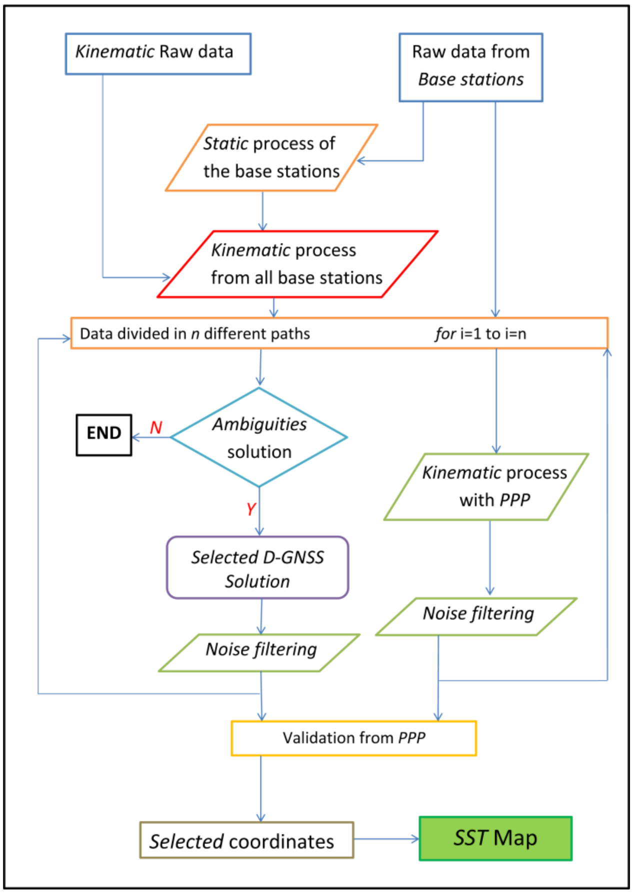

Figure 3. Illustration of the basic methodology of the first expedition [16, figure 16]

The raw data of the second expedition was resolved using the PPP method, while data noise was corrected using a special code. Ripple oscillations were corrected using data from the accelerometer, while the random noise was dealt with by testing successive moving average fitters, using the Savitzky-Golay method (Schafer, 2011). The tide was corrected using the tide gauge measurements and confirmed by the TASK software estimates. The final accuracy of the Sea Surface Topography estimates was calculated using the law of transmission of errors and was estimated at 1.3 cm. In contrast, the accuracy of the results of the first expedition was estimated at 5.43 cm. The main reason for this difference was that in the first expedition there was no reliable tide data and so it was estimated using data from remote stations (Lycourghiotis, 2017b).

Results and Discussion

Table 1 shows the results for the average value of the marine topography (MSL) in both expeditions. As can be observed, in the 12 years between the two expeditions there was an increase in the MSL of the common experimental area by 2.78 cm. This increase is generally in line with the estimates of other researchers (Meli, 2023). This fact confirms that the GNSS-on-boat method is suitable for SLR estimation. If we also consider that the method makes it possible to study, with extreme precision, marine areas that are not covered by the range of satellites, or coastal areas and closed seas where satellite methods fail, then we can say that a new field of research is opening.

Table 1. Mean sea levels in experimental areas. Differences in the common study area.

Mission	2010	2023	Differences
MSL (m) in their original study area	24.8534	24.6792	
MSL (m) in common area	24.6653	24.6931	+2.78 cm

Figure 4 shows the estimates of MSL Topography as obtained from the two research expeditions. On the top left we see the results of the first mission (2010). At the top right we see the results of the second mission (2023). While at the bottom right we see the results of both missions in their common study area. As can be seen, a small but statistically significant change in the shape of the sea surface is detected. The differences in the shape of the sea surface are particularly evident at points A and B (bottom right), where the slope of the topography and curves change significantly. Trying to estimate these differences statistically, we took a canvas of 42,546 points throughout the common study area and calculated the differences between the two estimates. From the analysis it emerged that the differences in the shape of the sea surface are statistically significant and reach the level of 8%.

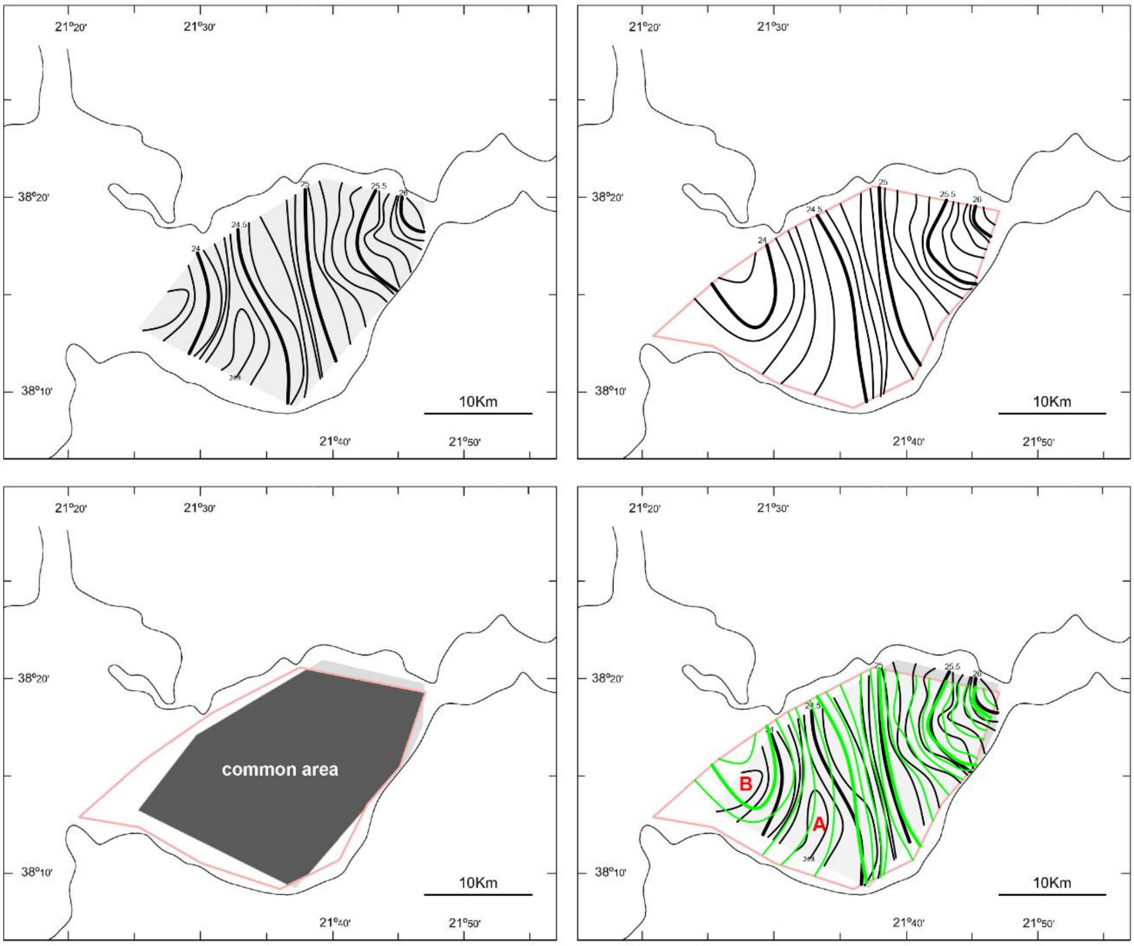

Figure 4. Results of the assessment of MTS from the two research expeditions in Patras Bay. (Above) Left and right show the first and second expeditions. (Bottom). Their common research area and comparison of their results. The contour interval of the contour lines is equal to 10cm. Heights were calculated above the WGS84 ellipsoid.

Despite the statistical significance of these differences, it would be risky to claim that the observed change in sea surface shape is due to climate change and SLR. The significant tectonic variability of the region could lead to such changes. We should also be wary of the small but significant differences observed in the results of the GNSS-on-boat analyses used in the two expeditions. In any case, the observations made here open up an important research question that future research is called upon to answer.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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