

**Long-Term Trends, Interannual
Variability and Seasonal Patterns of
Mean Sea Level in the Canary
Islands**

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Abstract

This study analyzes mean sea level variability in the Canary Islands from 1993 to 2022 using tide gauge and satellite altimetry data. During this period, both Las Palmas de Gran Canaria and Santa Cruz de Tenerife exhibited a significant sea level rise of 3.88 ± 0.52 and 4.19 ± 0.68 mm yr⁻¹, respectively. Comparison between tide gauge and altimetry records reveals slight land subsidence at both locations, approximately 0.5 mm yr⁻¹, contributing to the observed relative sea level rise. The spatial differences in the trends observed from altimetry appear to be associated with mesoscale ocean dynamics, particularly an increase in eddy activity along the Canary Eddy Corridor. Projections based on IPCC SSP scenarios suggest that sea level could rise by up to 395 mm in Santa Cruz and 365 mm in Las Palmas by 2050 under high-emission conditions. An additional 20 mm could be added due to land subsidence if it remains constant. Interannual variability is primarily correlated with the North Atlantic Oscillation (NAO); however Atlantic Multidecadal Oscillation (AMO) and the Atlantic Meridional Overturning Circulation (AMOC) indices also appears to correlate well with its low-frequency components. The seasonal cycle, driven primarily by steric effects, peaks in late summer and reaches a minimum in late winter, with its amplitude varying across the region. The seasonal amplitude is approximately 49.6 mm in Las Palmas and 70.2 mm in Santa Cruz.

1. Introduction

Changes in mean sea level are associated with some of the most severe impacts of climate change, including flooding, coastal erosion, saline intrusion, ecosystem loss, and an increased risk to infrastructure and services (IPCC, 2023). The global rise in sea levels has accelerated significantly over recent decades, driven primarily by thermal expansion of seawater and melting ice from glaciers and polar ice sheets. In Europe, it is estimated that more than 50 million people live in areas below 10 meters in altitude, making them particularly vulnerable to these variations (Neumann et al., 2015). Therefore, sea level is a variable of great relevance both for scientific research and for land use planning and public policy formulation.

Global mean sea level (GMSL) estimates are key indicators of ongoing global warming, but changes in regional sea level prove more relevant for local risk management (Kopp et al., 2015; Nicholls, 2011; Stammer et al., 2013; Woodworth et al., 2019). Regional or local mean sea level (LMSL) observations demonstrate significant spatial and temporal variability, posing a challenge for planning adaptation measures.

The Canary Islands are an example of a region that is particularly vulnerable to sea level rise because of their oceanic island characteristics. According to the IPCC Special Report, "Sea Level Rise and Implications for Low-Lying Islands, Coasts, and Communities" (Oppenheimer et al., 2019), island regions and archipelagos, are at a heightened risk due to their limited adaptive capacities, high concentrations of coastal infrastructures, and exposure to extreme wave and storm events. Despite these vulnerabilities, comprehensive studies focusing on sea level reconstructions and future projections for the Canary Islands specifically remain scarce (Fraile-Jurado et al., 2014; Marrero-Betancor et al., 2022).

Analyzing sea level variability requires studying the three main temporal scales commonly used in oceanographic research: long-term trends, interannual fluctuations, and seasonal cycles (e.g. Pugh & Woodworth, 2014; Biguino et al., 2024). These scales capture different driving mechanisms and are critical for understanding both the background rise in sea level and its shorter-term variability. The following sections briefly describe each of these components:

- **Long-term trends**

Most available data show a continuous rise in GMSL since the early 20th century, with a notable acceleration in recent decades (Frederikse et al., 2020). A significant number of authors have generated reconstructions of GMSL from tide gauge records (Church et al., 2011; Dangendorf et al., 2019; Ray & Douglas, 2011). The most recent study, by Frederikse et al. (2020), estimated a GMSL rise of 1.56 ± 0.33 mm yr⁻¹ between 1900 and 2018. However, since 1993, this rate has accelerated, reaching

$3.35 \pm 0.4 \text{ mm yr}^{-1}$, consistent with altimetric data (Hamlington, Frederikse et al., 2020).

The contributions of various drivers have been quantified through parameterizations and process-based models. These estimates suggest that approximately 50% of the observed global sea level rise is due to thermal expansion, while the remaining 50% is mainly attributed to glacier melt, the loss of ice from Greenland and Antarctica, and groundwater depletion (Gregory et al., 2013; Frederikse et al., 2020).

Long-term sea level changes exhibit a pronounced regional component, making it essential to distinguish between global and local changes (Gregory et al., 2019). While GMSL largely reflects global-scale processes such as thermal expansion and continental ice loss (Vermeer & Rahmstorf, 2009), local sea level is also affected by a combination of other factors (Hamlington, Gardner et al., 2020; Martínez-Asensio et al., 2019; Oppenheimer et al., 2019; Pfeffer & Allemand, 2016), including:

- Regional ocean dynamics (winds, currents, Kelvin and Rossby waves)
- Uneven distribution of ocean warming
- Geographic patterns of ice melt
- Vertical land motion

- **Interannual variability**

In addition to long-term trends, mean sea level exhibits interannual variability driven by processes operating over several years. Major contributing factors include climate modes such as the El Niño–Southern Oscillation (ENSO), which can cause sea level fluctuations of several centimeters at regional and global scales (Nerem et al., 2010). Other phenomena, such as the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO), also modulate sea level interannually, particularly in the North Atlantic and North Pacific (Volkov & van Aken, 2003; Hamlington et al., 2013). On smaller spatial scales, mesoscale eddies can produce short-term fluctuations that also affect interannual variability as well (Forget & Ponte, 2015; van Westen & Dijkstra, 2021).

- **Seasonal variability**

Sea level exhibits marked temporal variability on seasonal time scales. This seasonal signal is primarily driven by the thermal expansion of seawater during warmer months and its contraction during colder months, resulting in an annual cycle of sea level rise and fall (Forget & Ponte, 2015). In addition to this steric component, seasonal storage of water in the form of snow and ice, particularly in the Northern Hemisphere during winter, temporarily reduces ocean volume (Chen et al., 1998). This process, combined with seasonal wind stress and other atmospheric forcings,

significantly modulates sea level at regional scales (Vinogradov & Ponte, 2011). The combination of these factors can produce seasonal oscillations of mean sea level of several centimeters, with amplitudes that vary depending on geographic region and latitude (Hughes & Williams, 2010).

Considering the background discussed above, this study aims to address the lack of specific research and monitoring by conducting an in-depth analysis of the mean sea level variations in the Canary Islands region from 1993 to 2022. The analysis will examine the temporal and spatial variability in sea level using tide gauge records and satellite altimetry data. The results seek to enhance understanding of local sea level dynamics and provide more accurate projections for adaptation and policy development.

2. Data

2.1 Sea-level measuring systems

Although there is no universal definition of mean sea level, it is usually understood as the average height of the ocean surface relative to a terrestrial reference system. Currently, it is recommended that this average be calculated over intervals of at least one month, which are long enough to filter out tidal signals and meteorological disturbances (Gregory et al., 2019).

The time series used to analyze sea level variations are primarily derived from two sources: tide gauges and satellite altimetry. A summary of each data source is presented below.

- **Tide gauge records**

Until 1993, historical sea level records were exclusively derived solely from tide gauges, which measure changes in sea level relative to local terrain, typically situated in harbor areas. These data form the basis of the Permanent Service for Mean Sea Level global repository (PSMSL, <https://psmsl.org/data/>) (Holgate et al., 2013; PSMSL, 2025), enabling the estimation of long-term trends from the early 20th century at sites with sufficiently long time series. The PSMSL implements a standardized processing procedure (Pugh & Woodworth, 2014), which includes filtering hourly data to obtain daily values, and their subsequent monthly or annual arithmetic mean. In addition, it employs a conventional reference level designated as the Revised Local Reference (RLR), normally defined about 7 meters below mean sea level to avoid negative values in the series.

Tide gauge measurements have two main limitations: (1) limited spatial coverage, as they are predominantly located along coastlines (2) sensitivity to local vertical terrain movements. This latter limitation can be overcome by co-locating Global Navigation Satellite System (GNSS) stations near tide gauges (Wöppelmann & Marcos, 2016).

- **Satellite altimetry Data**

Development of satellite altimetry, represented by the launch of TOPEX/Poseidon in 1993, allowed to obtain continuous global measurements of sea level. In altimetry, sea level is measured as the distance between the ocean surface and a global reference ellipsoid (such as WGS84; Fu & Cazenave, 2001). Altimetric series near tide gauge stations generally show strong agreement on scales of days or greater, mainly in oceanic islands (Williams & Hughes, 2013), while agreement may be low in continental coastal regions due to the influence of local processes (Vinogradov & Ponte, 2011).

Altimetric data are available from several international repositories. One of the main sources is the Copernicus Marine Environment Monitoring Service (CMEMS, <https://data.marine.copernicus.eu/products>), which provides global and regional products derived from missions such as Jason-3, Sentinel-3, and CryoSat-2. Additional datasets are available through the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO+), managed by CNES, and NASA's PO.DAAC (Physical Oceanography Distributed Active Archive Center), which hosts data from missions including TOPEX/Poseidon, Jason-1/2/3, and Sentinel-6.

2.2 Data Sources and Repositories

Four datasets were used in this study:

- **Monthly mean sea level records** from the tide gauges at Las Palmas de Gran Canaria (LP) and Santa Cruz de Tenerife (SC) shown in **Figure 1**, covering the period from January 1993 to January 2023, were obtained from the PSMSL. These two stations were selected due to the length and completeness of their time series, which ensures the robustness of sea level trend estimation. Data from PSMSL was preferred because it undergo a rigorous quality control process that enhances reliability, particularly important when merging time series recorded with different types of instruments, as often occurs when equipment is updated or replaced.
- **Monthly sea surface height above the ellipsoid derived from satellite altimeter** for the Canary Islands region was obtained from the *Global Ocean Gridded L4 Sea Surface Heights and Derived Variables – Reprocessed* dataset provided by the

CMEMS. This product offers monthly sea surface height data and related variables from 1993 to 2024, with a spatial resolution of $0.25^\circ \times 0.25^\circ$. It was selected due to the stability and homogeneity of the sea level record, which is based on a consistent two-satellite constellation. These data were used to study the spatial variability of mean sea level in the region shown in **Figure 1**.

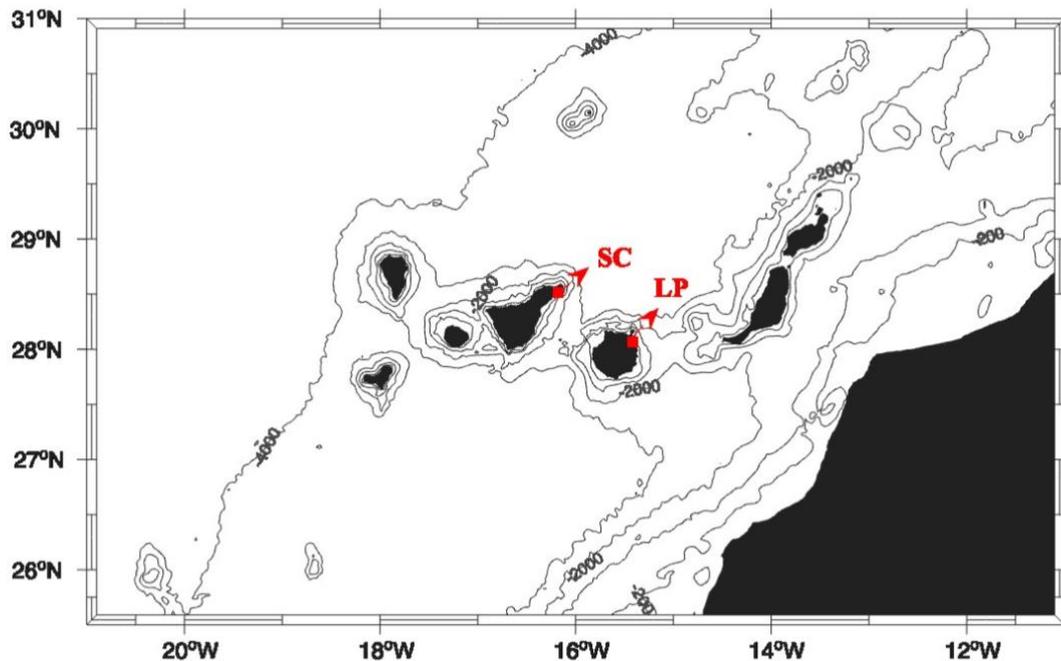


Figure 1: Study area and bathymetry. The markers indicate the locations of the tide gauges at Las Palmas de Gran Canaria (LP) and Santa Cruz de Tenerife (SC).

- **Sea surface temperature (SST)** for the study area was obtained from the *Multi-Observation Global Ocean ARMOR3D L4 analysis and multi-year reprocessed* product provided by the CMEMS. The dataset covers the period 1993–2023 and includes monthly fields of temperature, salinity, sea level, geostrophic currents, and mixed layer depth, all provided on a regular $1/8^\circ$ grid.
- **Monthly time series of GMSL** variation from 1900 to 2018 were obtained from the reconstruction developed by Frederikse et al. (2020, available in: <https://zenodo.org/records/6067895>). This model combines observations of ocean mass (barystatic component) and thermal expansion (thermosteric component), along with tide gauge records from around the globe corrected for vertical land motion and gravitational effects. The resulting dataset is illustrated in **Figure 2**.

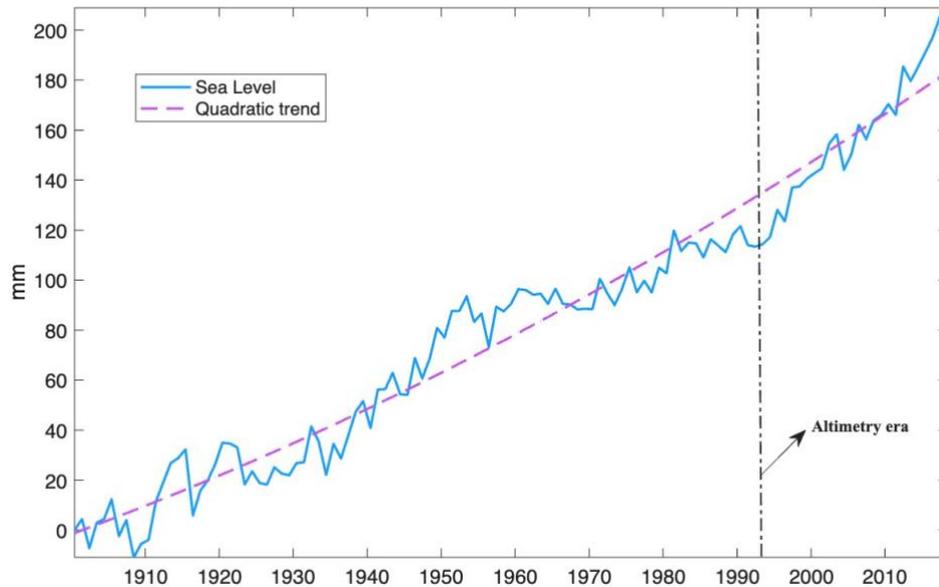


Figure 2: Global Mean Sea Level (GMSL) time series including quadratic trend based on the reconstruction by Frederikse et al. (2020) for the period 1900-2018. The altimetry era is indicated.

In addition, complementary information was obtained for comparison with other sources:

- **Vertical land motion** data derived from GNSS measurements were obtained from the PSMSL and the Système d'Observation du Niveau des Eaux Littorales (SONEL). These data are available at <https://psmsl.org> and <https://www.sonel.org>. The results of two recent studies by Barbero et al. (2021) and Pfeffer and Allemand (2016) were also used.
- **Sea level rise projections** produced by NASA for the most recent Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2023). These projections, based on historical reconstructions and coupled ocean–cryosphere model simulations, provide estimates of future sea level changes through the year 2150. They are accessible via an interactive tool at <https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool> (NASA, n.d.).

3. Methodology

The analysis of mean sea level variability in the Canary Islands region was carried out using MATLAB® as the primary computational tool. All-time series processing, statistical analyses, visualizations, and spectral evaluations were performed within the MATLAB environment.

First, the monthly time series from the tide gauges and the satellite altimetry were examined and harmonized in length to allow for direct comparison. As shown in **Figure 3**, the tide gauge records contain some data gaps. Overall, the data coverage is good, with no more than two consecutive missing months, except at the LP station, which has four consecutive missing months between the end of 2018 and the beginning of 2019. These missing values were linearly interpolated at the same time steps as the satellite altimetry data to facilitate a consistent comparison of the two datasets.

The inverted barometer effect (i.e., sea level variations caused by the hydrostatic response of the ocean to changes in atmospheric pressure) was not removed from the tide gauge records. This reflects the study's focus on analyzing effective sea level variability rather than isolating individual forcing mechanisms.

Linear trends were estimated using least-squares regression, and 95% confidence intervals were computed to assess their statistical significance. Additionally, the statistical significance of the trend slope was evaluated by computing the associated *p-value*. All-time series used in this study yielded statistically significant trends (*p-value* < 0.05). To investigate sea level variability across different temporal scales, standard procedures recommended by Pugh and Woodworth (2014) were applied:

1. **Trend estimation:** computed by applying a linear least-squares fit to the monthly sea level time series. To avoid biases due to incomplete seasonal cycles, years with missing months at the beginning or end of the series were excluded from the analysis.
2. **Interannual anomalies:** obtained by subtracting the long-term linear trend from the annual mean sea level values.
3. **Seasonal anomalies:** obtained by subtracting the annual mean sea level from the monthly mean sea level values.

Finally, spectral analysis was conducted using Welch's method to identify dominant frequencies and characterize interannual variability. The MATLAB function `pwelch` was used for this purpose, applying a Hamming window to minimize spectral leakage and improve frequency resolution.

4. Results

4.1. Long-term variability

Figure 3 illustrates the variation in the monthly mean sea level recorded by the LP and SC tide gauges from 1993 to 2022 referenced to the mean sea level for the period 1995-

2014, as the IPCC states in its latest Assessment Report (IPCC, 2023). It also shows the corresponding time series derived from satellite altimetry for nearby grid cells. There is clear agreement between the tide gauge and altimetry records. The figure also shows the annual mean sea level, revealing that although the mean sea level is rising overall, the increase is not monotonic. Specifically, the rate of sea level rise slowed from approximately 2000 to 2015, then accelerated again from 2015 to 2022.

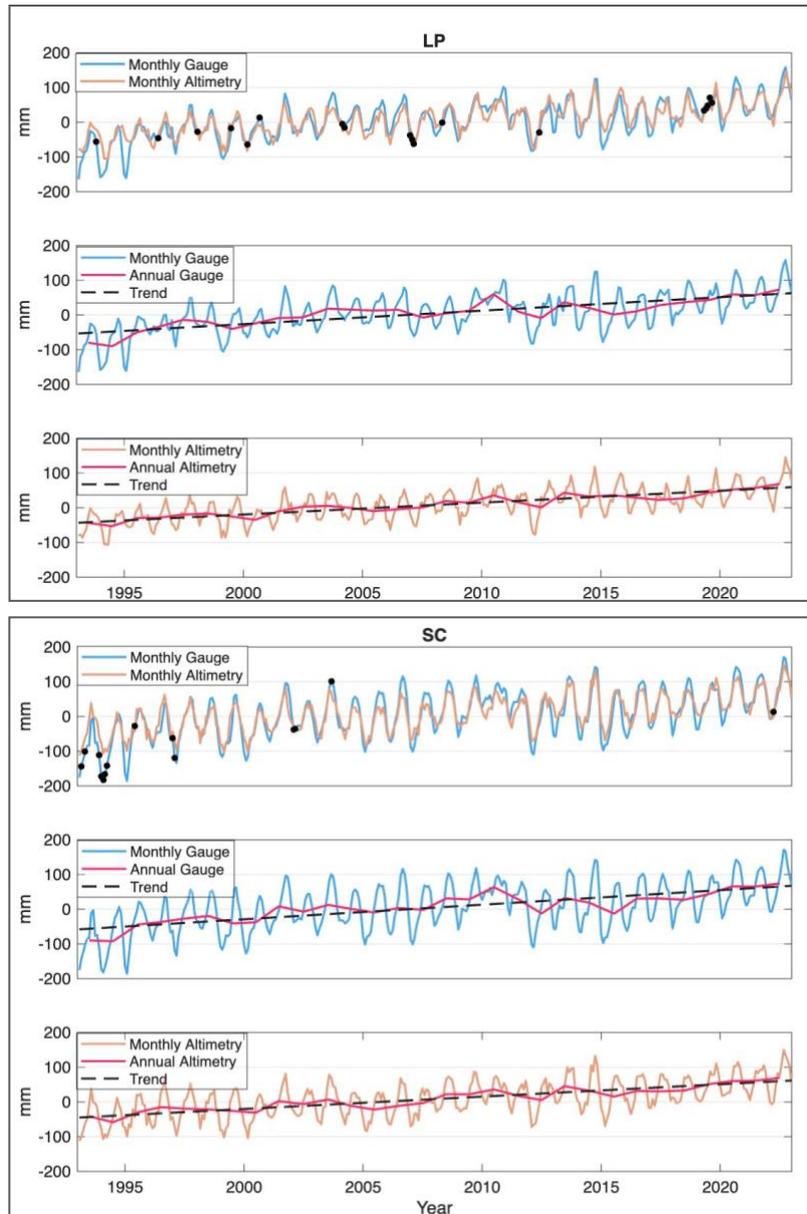


Figure 3: Tide gauge and nearby grid-cell altimetry data for Las Palmas (LP) and Santa Cruz (SC), showing monthly means, annual means, and linear trends for the period 1993–2022. Time series are referenced to mean sea level for the period 1995–2014, same reference level used by IPCC in its last Assessment Report (AR6). Black dots indicate gaps in the tide gauge records.

Table 1 presents the mean sea level rise rates obtained through linear fitting of the monthly sea level time series, as well as the differences between the values derived from tide gauge and altimetry data. At both LP and SC stations, this difference is positive, suggesting vertical land subsidence at these locations with an estimated rate close to 0.5 mm yr^{-1} .

Table 1: Local sea level rise trends at LP and SC (1993–2022), and estimated vertical land motion based on the difference between tide gauge and altimetry records. Values are expressed in $\text{mm yr}^{-1} \pm 95\%$ confidence interval.

	<i>LP</i>	<i>SC</i>
Tide gauge trend	3.88 ± 0.52	4.19 ± 0.68
Altimetry trend	3.43 ± 0.39	3.56 ± 0.50
Difference	0.46 ± 0.32	0.63 ± 0.34

The mean sea level trend was calculated for each grid cell in the altimetric dataset (**Figure 4**). The results reveal complex spatial variability in sea level rise at the scale of typical mesoscale phenomena ($\sim 100 \text{ km}$), with values ranging from 3 to 4 mm yr^{-1} .

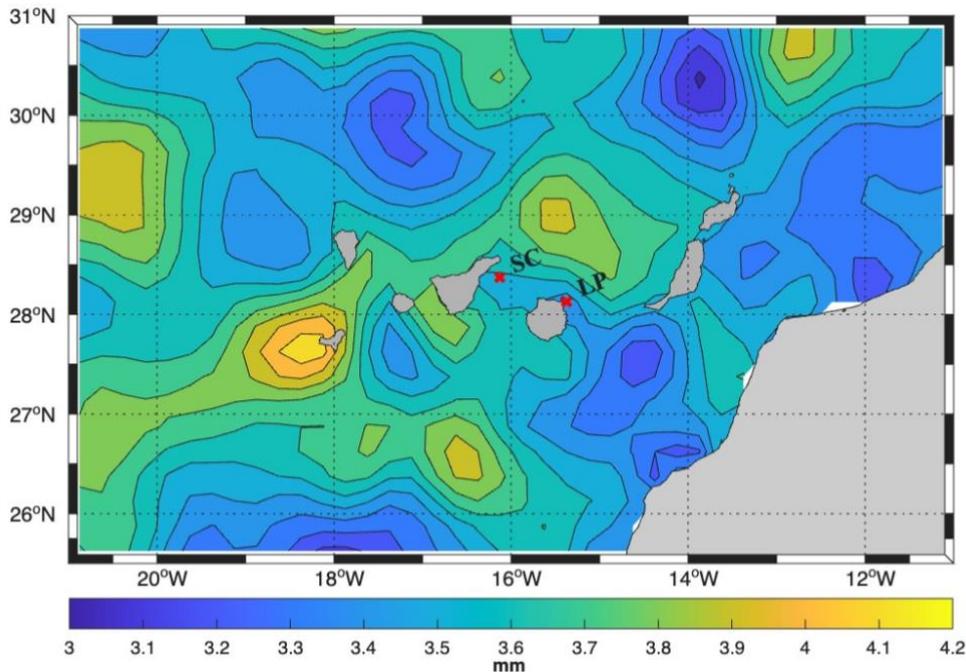


Figure 4: Sea level trend in the Canary Islands region for the period 1993-2022. Location of nearby tide gauges grid-cells are highlighted as well.

To further investigate this variability, we also calculated the trend in Eddy Kinetic Energy (EKE), which is provided as an output variable in the product used (see Data section) and serves as a proxy for mesoscale ocean variability driven by eddies. The results (**Figure 5**) show a positive trend in EKE, particularly in the Canary Eddy Corridor (Sangrà et al., 2009), indicating an intensification of mesoscale activity in the region.

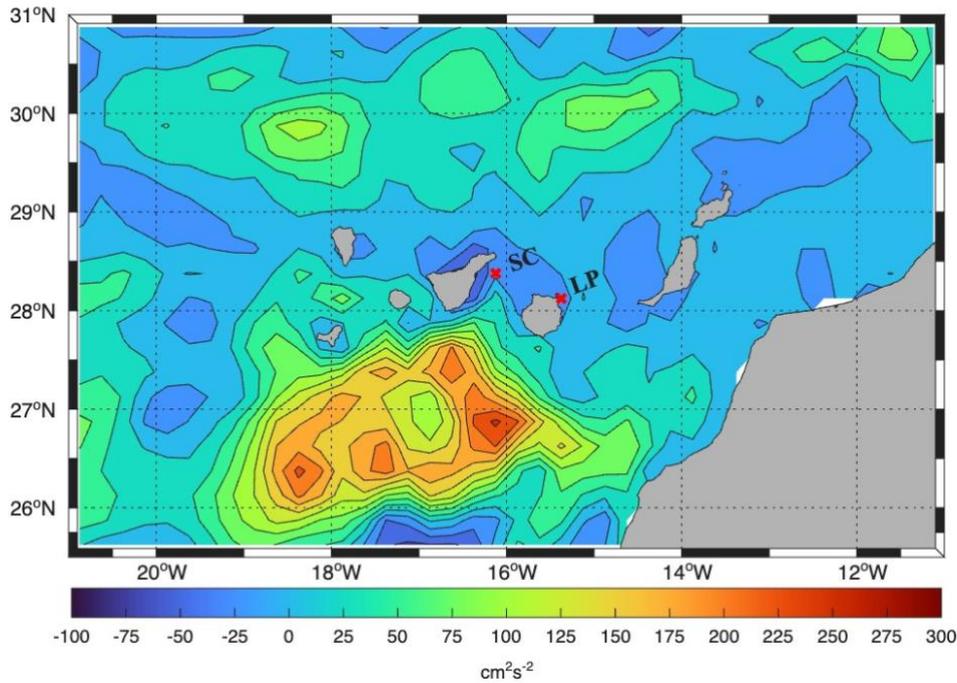


Figure 5: Eddy Kinetic Energy (EKE) trend in the Canary Islands region for the period 1993-2022 expressed in cm^2s^{-2} . Location of nearby tide gauges grid-cells are highlighted as well.

4.2. Interannual anomalies

The interannual sea level anomaly was calculated by removing the linear trend from the annual mean sea level time series (Pugh & Woodworth, 2014). The resulting anomaly was then normalized by dividing the residuals by their standard deviation. **Figure 6** displays this normalized anomaly and compares it with four climate indices (each also detrended to focus on interannual variability): (a) the NAO index, which quantifies the difference in normalized sea-level pressure between the subtropical high-pressure system near the Azores and the subpolar low near Iceland; (b) the Atlantic Multidecadal Oscillation (AMO) index, derived from spatially averaged North Atlantic SST anomalies (typically 0-60°N) after removing the global mean SST signal, represents natural multidecadal variations between warm and cool phases. (c) the East Atlantic (EA) pattern, defined as the second principal component of 500 hPa geopotential height anomalies over the North Atlantic, and (d) the Atlantic Meridional Overturning Circulation (AMOC), which quantifies the maximum value of vertically integrated meridional volume transport at 26.5°N.

Although some relationship can be observed between sea level at the LP and SC tide gauges and the four climate indices, the strongest correlation is found with the NAO (0.53 for LP and 0.61 for SC). In the case of the AMO and AMOC, however, its evolution resembles only the low-frequency variation in sea level and not the higher-frequency or rapid oscillations.

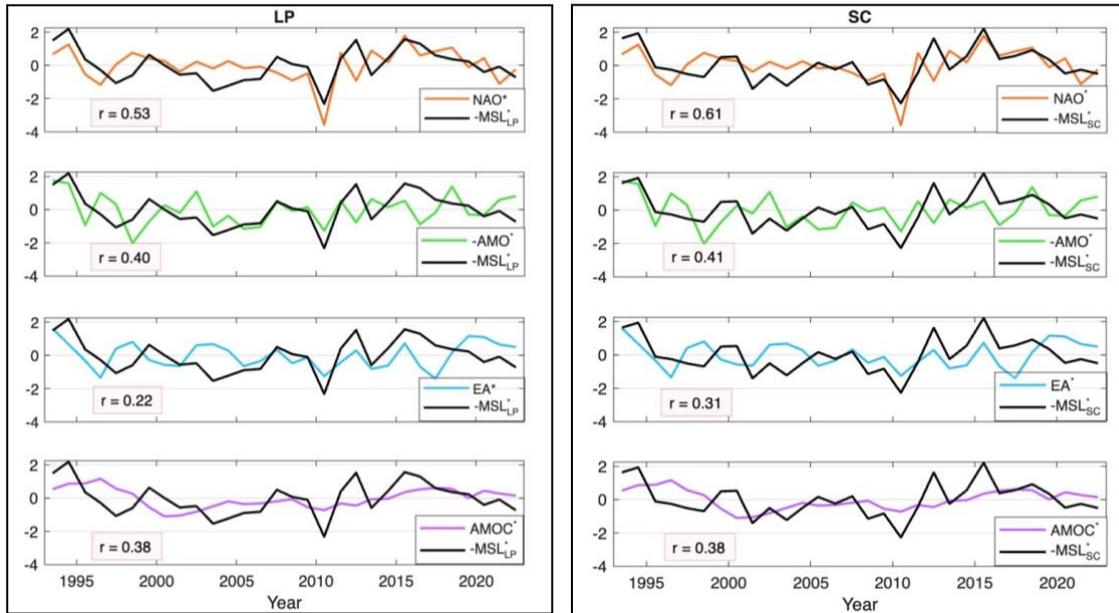


Figure 6: Interannual normalized sea level anomalies ($-MSL^*$, in black) in LP for the period 1993-2022 compared with four climate indices: (a) the NAO, (b) the AMO, (c) the EA pattern, and (d) the AMOC.

The spectral analysis of the interannual sea level anomaly time series reveals the presence of two dominant frequency bands at both study locations (**Figure 7**). The first band, between 0.25 and 0.3 cycles per year (cpy), corresponds to rapid oscillations with periods of approximately 3–4 years. This high-frequency component remarkably correlates with variations in the NAO. The second band is a low-frequency band associated with 20-30 year periods. In **Figure 6**, this band appears superimposed on the higher-frequency variability, and it notably correlates with variations in AMOC.

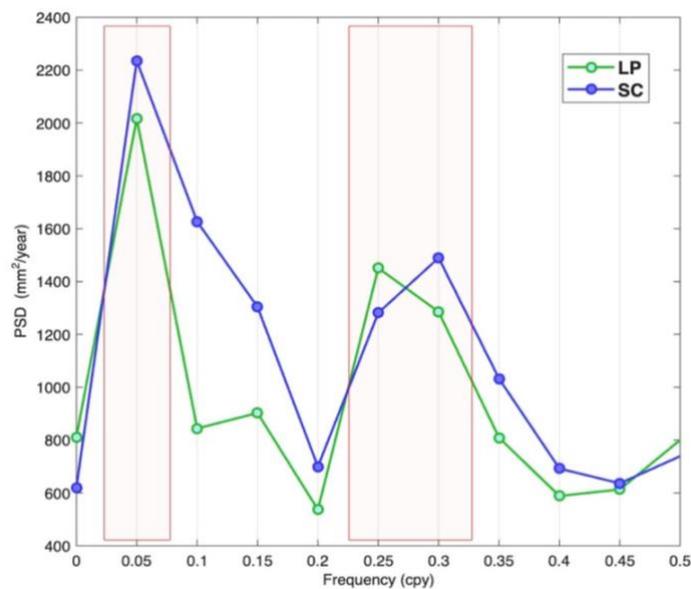


Figure 7: Power spectral density (PSD) of interannual sea level variability obtained using Welch's method. Frequency is expressed in cycles per year (cpy) and dominant frequencies are highlighted in red.

4.3. Seasonal anomalies

To calculate the seasonal sea level anomaly, the annual mean sea level was subtracted from each monthly value within the corresponding year (Pugh & Woodworth, 2014). The resulting anomalies were then averaged over the entire study period (1993–2022) for each calendar month, yielding a mean seasonal cycle. The results at both LP and SC stations, derived from tide gauge records and satellite altimetry in the study area (**Figure 8**), exhibit a consistent pattern: sea level typically reaches its annual maximum between September and October and its minimum between February and April. The signal from satellite altimetry exhibits a lower seasonal range (81.14 mm for LP and 101.02 mm for SC), compared with the tide gauge data (99.15 mm for LP and 144.40 mm for SC) likely due to the spatial smoothing applied in the reanalysis product which tends to attenuate local variability.

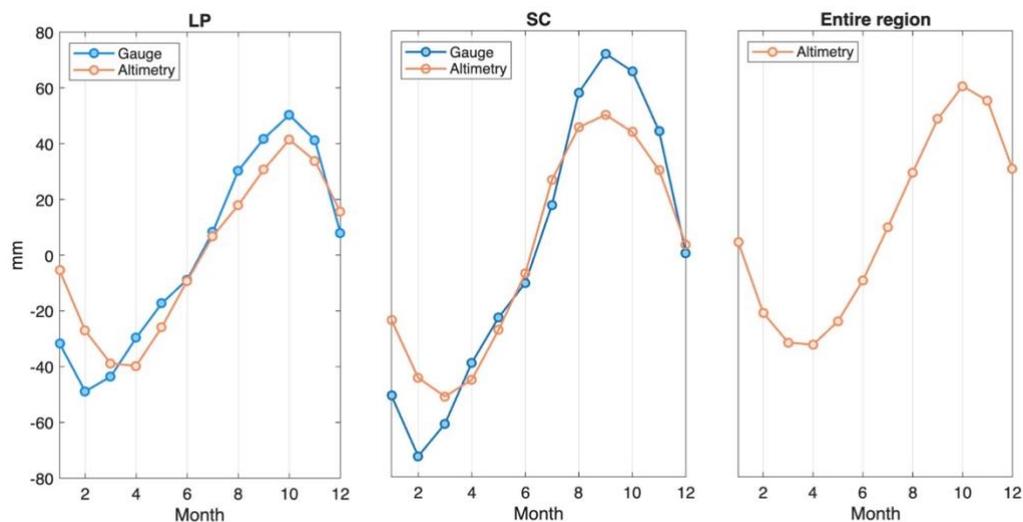


Figure 8: Left and center panels: seasonal sea level anomalies derived from tide gauges (blue lines) and satellite altimetry at the grid cells nearest to the tide gauges (red lines). Right panel: spatially averaged satellite altimetry over the entire study area.

The same procedure was applied to the spatially averaged sea surface temperature dataset for the Canary region, obtained from the Multi-Observation Global Ocean ARMOR3D L4 Copernicus product (see Data section). The results (**Figure 9**, bottom) evidence that the observed seasonal cycle is primarily driven by steric effects as sea surface temperatures peak in late summer and early autumn. In contrast, cooler temperatures in late winter and early spring reduce thermal expansion, resulting in lower sea levels. Additional contributions from seasonal wind stress and atmospheric pressure variability may further modulate coastal sea level on monthly timescales (Biguino et al., 2024) and could account for the small differences observed between the two stations.

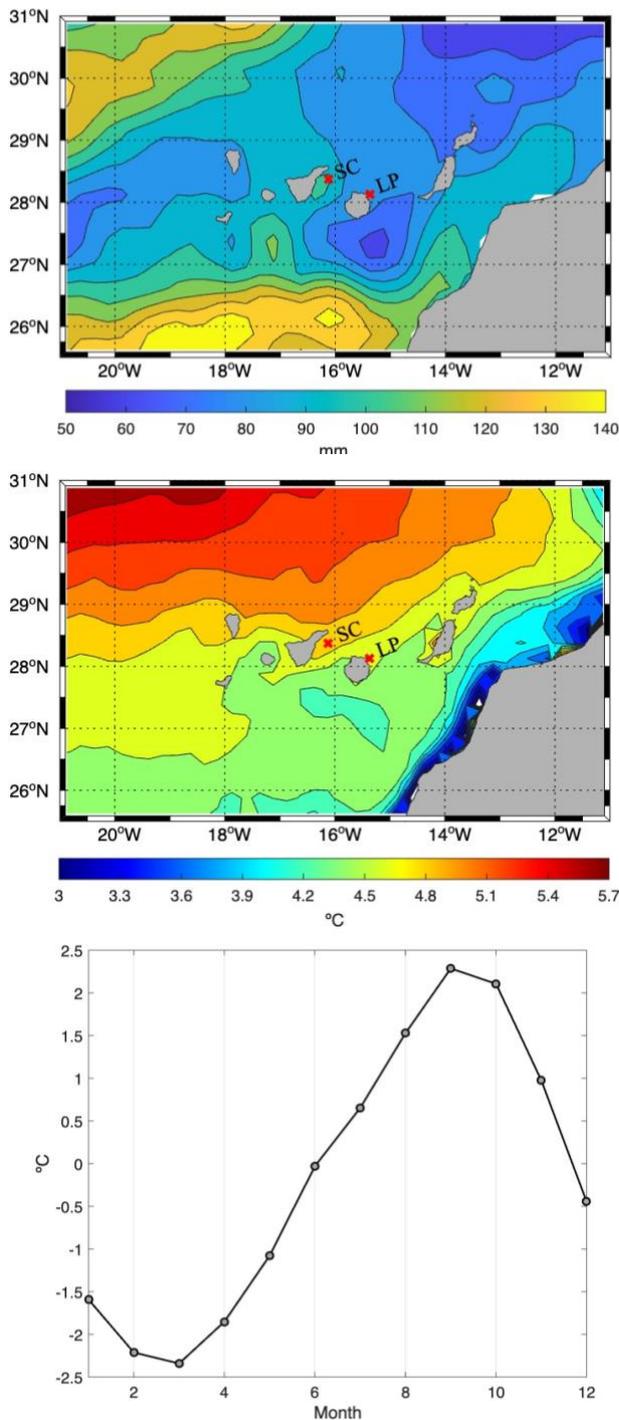


Figure 9: (Top) range of the seasonal oscillation in sea level across the entire study area., (middle) seasonal SST changes and (bottom) range of the SST seasonal cycle across the entire study area for the period 1993-2022.

Figure 9 (top) shows range of the seasonal oscillation (defined as the difference between the maximum and minimum values of the mean seasonal cycle) across the study area. This reveals significant spatial variability. A band of minimum height, ranging from approximately 60 to 80 mm, extends from around 27–28°N on the western edge of the domain towards the northeast. This band is flanked by two regions of maximum height: one to the south, where values reach 140 mm near 26°N, and another to the northwest, where values are around 120 mm.

When considering the seasonal oscillation of SST (**Figure 9**, middle), the spatial pattern does not fully align with the SST pattern despite the temporal evolution of the seasonal cycles are very similar (see **figures Figure 9**, bottom, and **Figure 8**). These results suggest that additional local factors may influence the spatial variability of the seasonal cycle in this region.

One such factor may be the mesoscale activity. The seasonal variation of EKE shows a wider range south of the Canary Islands, extending southwestward (**Figure 10**). This pattern is consistent with the previously observed intensification of eddies in the Canary Eddy Corridor over the past 30 years (Barceló-Llull et al., 2024).

Studying the seasonality of EKE could help to explain some of the variability in the spatial discrepancy between SST and sea level. Similar to SST and sea level (**Figure 8** and **Figure 9**), EKE maximum can be observed in September and October, with significant variations occurring along the southern edge of the study region between 25.5° and 28°N (**Figure 10**).

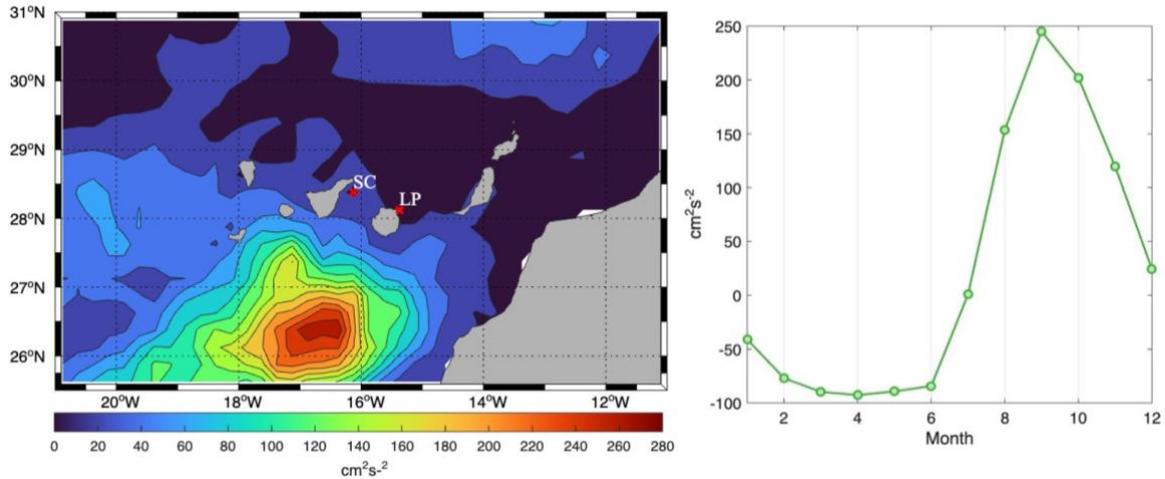


Figure 10: Eddy Kinetic Energy (EKE) seasonal shifts in the Canary Islands region for the period 1993-2022 expressed in cm^2s^{-2} . (Left) Spatial distribution of seasonal changes and (right) range of these changes across the study area. Location of nearby tide gauges grid-cells are highlighted as well.

4.4. Future projections

One of the objectives of this study is to estimate the expected mean sea level change in the Canary Islands by the middle of the 21st century, based on recent observational data analyzed in this paper. This projection relies on extrapolating the relationship between local sea level records, corrected for vertical land motion, and the most recent reconstructed GMSL time series into the future (Frederikse et al., 2020). Assuming that the long-term local sea level rise will not necessarily be linear but rather proportional to global sea level rise, a linear relationship between local and global sea level series is expected (Fraile-Jurado et al., 2014). The extrapolation can then be performed using a simple linear regression model, with the GMSL series as the input variable and the LMSL as the response variable (**Figure 11**).

We used three future scenarios proposed in the Sixth Assessment Report (IPCC, 2023) - SSP1-1.9 (the most optimistic), SSP2-4.5, and SSP5-8.5 (the most pessimistic)- to estimate sea-level change up to 2050. These scenarios represent possible future climate trajectories based on demographic changes, economic development, urbanization patterns, greenhouse gas emissions, and the extent of climate intervention policies. The resulting projections (**Figure 11** and **Table 2:**) show a progressive rise in sea levels depending on the scenario. In the best-case scenario (SSP5-1.9), values close to 200 mm

are reached, whereas in the worst-case scenario, values are near 400 mm. The estimates, which include uncertainty intervals, show that the LP station is slightly less sensitive than the SC station.

Nonetheless, the sea-level rise observed at both locations closely follows global projections.

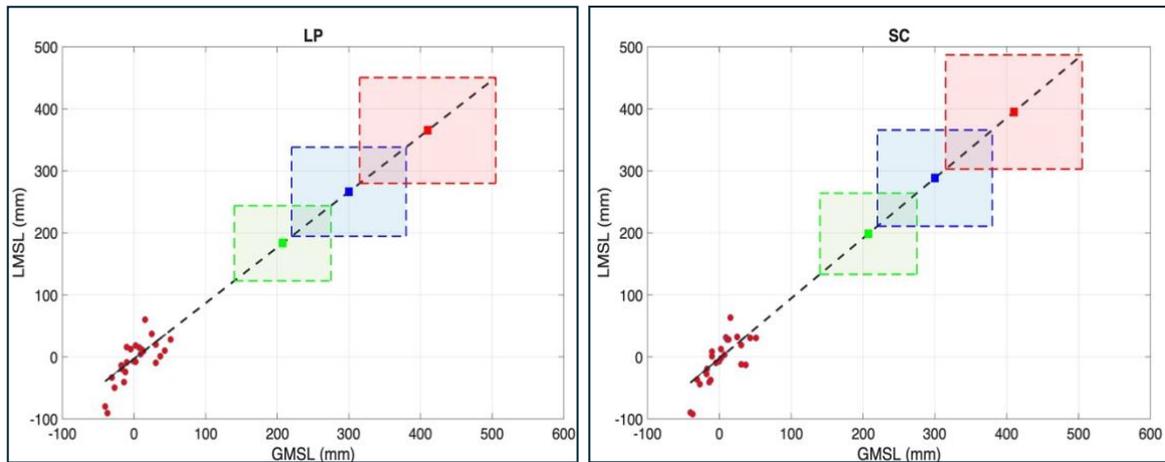


Figure 11: Regression between local mean sea level rise at Las Palmas de Gran Canaria (left) and Santa Cruz de Tenerife (right), and GMSL. The dashed line represents the linear relationship extrapolated to 2050. Colored squares show projected mean sea level ranges under SSP1-1.9 (green), SSP2-4.5 (blue), and SSP5-8.5 (red).

Table 2: Projected mean sea level rise by 2050 for LP and SC tide gauges expressed in mm. The results for three SSP scenarios, along with their associated uncertainties, are shown

	<i>LP</i>	<i>SC</i>
SSP1-1.9	183.22 ± 60.62	198.60 ± 65.45
SSP2- 4.5	266.29 ± 71.85	288.29 ± 77.57
SSP5- 8.5	365.08 ± 85.32	394.94 ± 92.11

5. Discussion

5.1. Long-term trend

Results from tide gauge and satellite altimetry data indicate a rising trend in sea level at both locations during the period 1993–2022. At the LP station, the trend is 3.88 ± 0.52 mm yr⁻¹ based on tide gauge data, and 3.43 ± 0.39 mm yr⁻¹ from altimetry. At the SC station, the corresponding values are 4.19 ± 0.68 mm yr⁻¹ and 3.56 ± 0.50 mm yr⁻¹, respectively. These rates are slightly higher than those obtained by Marrero-Betancor et al. (2022) for the region from 1993 to 2019, as well as higher than those reported for the

GMSL by Frederikse et al. (2020), who estimated $3.35 \pm 0.34 \text{ mm yr}^{-1}$ for the period 1993–2018, and by Dangendorf et al. (2019), who found $3.1 \pm 0.3 \text{ mm yr}^{-1}$ for 1993–2015.

The altimetry results reveal complex spatial variability in mean sea level rise at the scale of typical mesoscale processes. A closer inspection shows that relative minima south of the islands coincide with locations where cyclonic eddies are frequently observed, while relative maxima correspond to areas typically dominated by anticyclonic eddies (Aristegui et al., 1994; Sangrà et al., 2005; Sangrà et al., 2007; Sangrà et al., 2009; Barceló-Llull et al., 2017; Cerdán-García et al., 2024), as approximately indicated in **Figure 12**. This finding is consistent with the observed positive trend in eddy kinetic energy (EKE) within the Canary Eddy Corridor, suggesting that the intensity of eddy activity has increased in this region over the study period, thereby influencing the spatial pattern of sea level trends. This finding aligns with the reported intensification of global ocean EKE over the past three decades, based on satellite altimetry observations (Barceló-Llull et al., 2024).

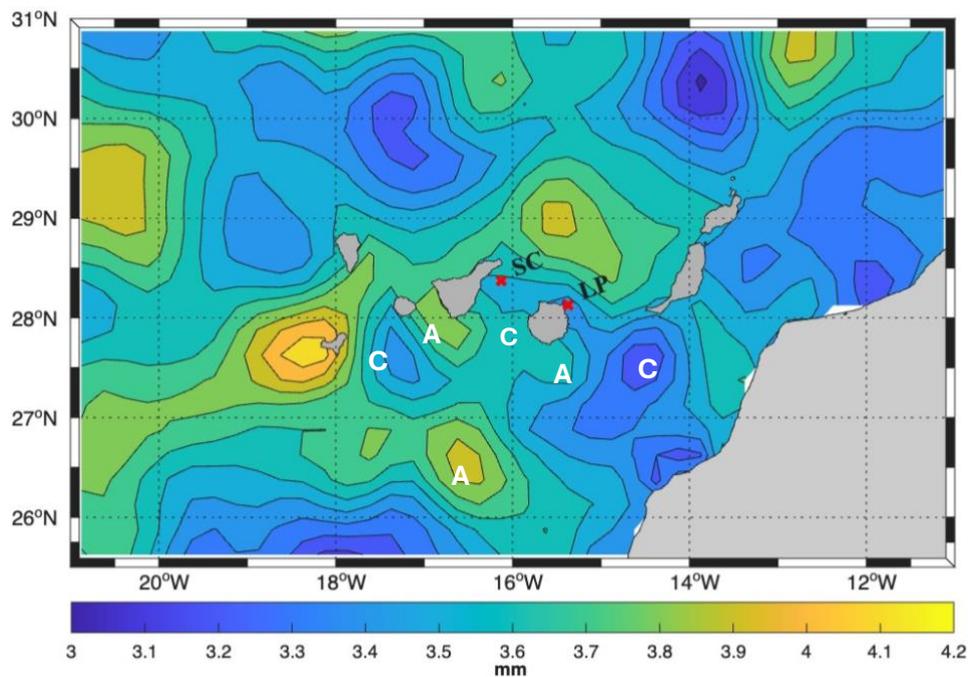


Figure 12: Sea level trend in the Canary Islands region for the period 1993–2022, with the approximate frequent locations of cyclonic (C) and anticyclonic (A) eddies indicated, based on observations reported in the literature (e.g., Aristegui et al., 1994; Sangrà et al., 2005, 2007, 2009; Barceló-Llull et al., 2017).

5.2. Vertical land motion

The vertical land motion estimates derived from the difference between altimetry time series and tide gauge records indicate negative trends of -0.46 ± 0.32 mm yr⁻¹ for Las Palmas de Gran Canaria and -0.63 ± 0.34 mm yr⁻¹ for Santa Cruz de Tenerife. These results confirm the presence of subsidence at both locations, contributing approximately half a millimeter per year to the relative sea level rise.

Several previous studies have also reported vertical land motion in the Canary Islands, although with varying results, as summarized in **Table 3**. Among them, Pfeffer and Allemand (2016) and Barbero et al. (2021) report significantly higher rates of subsidence, whereas GNSS data from the SONEL network and estimates from the PSMSL database yield values closer to ours, particularly for Tenerife. These discrepancies could be explained by methodological differences or limitations in data availability and temporal coverage.

Table 3: Summary of vertical land motion results obtained from previous studies and databases, compared with the present study. Results are expressed in mm yr⁻¹, including their uncertainty intervals and the corresponding time periods.

	<i>LP</i>	<i>SC</i>	PERIOD
Pfeffer & Allemand (2016)	-1.92 ± 0.48	-2.48 ± 0.33	1992-2013
Barbero et al. (2021)	-1.68 ± 0.81	-2.40 ± 0.39	2000-2015(LP) 2008-2015 (SC)
GNSS (SONEL)	Not robust	-1.55 ± 0.20	2007-2014
PSMSL	Not robust	-0.59 ± 0.3	2007-2023
Present study	-0.46 ± 0.13	-0.63 ± 0.19	1993-2022

5.3. Interannual variability

Climate modes such as those represented by the NAO, the AMO, the EA pattern, and the AMOC significantly correlate with interannual sea level variability through coupled atmospheric and oceanic processes (Han et al., 2017). Our results indicate that, while some degree of relationship exists between sea level variations at the LP and SC tide gauges and these four climate indices, the strongest correlation is observed with the NAO, which shows correlation coefficients of 0.53 for LP and 0.61 for SC. The NAO's direct modulation of regional atmospheric circulation patterns, including wind stress, storm

track positioning, and pressure distribution over the North Atlantic, likely causes this strong correlation. These patterns can significantly affect coastal sea levels on interannual timescales.

The EA pattern also influences sea level variability, though to a lesser degree compared to the NAO, possibly due to its secondary role over the North Atlantic (Martínez-Asensio et al., 2014). On the other hand, the AMO and the AMOC appear to be primarily linked to the lower-frequency component of sea level variability. This connection is consistent with the longer timescale at which both climate modes operate, involving deep ocean processes and large-scale meridional heat distribution. However, the AMO shows higher correlation coefficients either at LP (0.40) and SC (0.41) stations than the AMOC does. This frequency-dependent influence underscores the importance of considering different climatic drivers when interpreting regional sea level variability.

5.4. Seasonal cycle

The seasonality of local sea level is primarily driven by temperature-induced expansion and contraction of ocean water (Forget & Ponte, 2015; Gregory et al., 2013). In this study, the analysis of spatially averaged altimetry and sea surface temperature data for the Canary region has allowed us to identify this pattern, showing that variations in sea level and ocean temperature are closely coupled, as previously noted by Marrero-Betancor et al. (2022).

However, the spatial analysis reveals that this behavior is not uniform across the region. The differences observed in the magnitude and distribution of seasonal anomalies suggest that, in addition to temperature, other factors are modulating sea level, possibly including processes related to regional ocean dynamics (Hamlington, Gardner et al., 2020).

The results obtained for EKE seasonality indicate that mesoscale eddies may significantly influence the spatial distribution of sea level height seasonality, particularly in the southern region where the Canary Eddy Corridor is located. Therefore, mesoscale eddies have a direct impact on sea level observations in the Canary Islands, as previously proposed by Navarro-Pérez and Barton (2001) for this region, and by Firing and Merrifield (2004) for another island region, such as Hawaii.

5.5. Future projections

The implementation of the IPCC's SSP scenarios (IPCC, 2023) for 2050 has allowed estimation of potential sea level rise at the two studied locations. Under the most pessimistic scenario (SSP5-8.5), projected sea level rise could exceed 390 mm in SC and 365 mm in LP. These figures slightly differ from the estimates provided by NASA's Sea Level Projection Tool, summarized in **Table 4**.

The NASA projections for the more optimistic scenarios (equivalent to SSP1-1.9 and SSP2-4.5) are slightly higher than our estimates, although they present notably broader uncertainty margins. However, under the most pessimistic scenario (equivalent to SSP5-8.5), our results indicate a higher sea level rise compared to NASA’s estimates. Furthermore, it is noteworthy that NASA’s tool assigns identical values to both locations, despite the known spatial variability within the Canary region driven by local oceanographic processes and differential land subsidence. This suggests that NASA’s projections might be overly generalized for local-scale applications, whereas our study provides estimates with narrower error margins, consistent with the significant spatial variability observed in the Canary Islands.

Finally, it should be noted that if land subsidence continues, it will lead to an additional increase in relative sea level. Assuming a constant rate equal to that observed in this study, this would imply an extra rise of approximately 20 mm by 2050 at both the LP and SC stations.

Table 4: Comparison of mean sea level rise projections estimated in the present study with those provided by NASA for the same locations (LP and SC) and Shared Socioeconomic Pathways (SSP 1.9, 4.5, and 8.5). Results are expressed in mm, including their uncertainty intervals. Note that NASA obtains same results for both locations.

Scenario	NASA projection for 2050		
	(LP and SC)	<i>LP</i>	<i>SC</i>
SSP1-1.9	260 (170–360)	183.22 ± 60.62	198.60 ± 65.45
SSP2-4.5	280 (190–380)	266.29 ± 71.85	288.29 ± 77.57
SSP5-8.5	310 (220–400)	365.08 ± 85.32	394.94 ± 92.11

6. Conclusions

This study provides a detailed analysis of mean sea level variability in the Canary Islands from 1993 to 2022 by combining tide gauge and satellite altimetry data. Comparison with external projections confirms that the Canary Islands follow the global pattern of accelerated sea level rise (Dangendorf et al., 2019; Frederikse et al., 2020) but exhibiting notable spatial heterogeneity. This heterogeneity appears closely linked to mesoscale ocean dynamics, particularly eddy activity within the Canary Eddy Corridor, as evidenced by the positive trend in eddy kinetic energy (EKE).

Vertical land motion contributes to the observed relative sea level trends, with subsidence detected at both locations. Although these rates are modest ($\sim 0.5 \text{ mm yr}^{-1}$), their effect accumulates over time and must be considered in local risk assessments.

Seasonal sea level variability is primarily driven by steric effects, as evidenced by the close relationship between sea surface temperature (SST) and sea level. However, the spatial patterns of seasonal amplitude differ between SST and sea level, suggesting the involvement of additional oceanographic processes. In particular, the seasonal increase in eddy kinetic energy (EKE) in the Canary Eddy Corridor points to a potential influence of mesoscale eddies on the seasonal sea level signal.

The study shows that interannual sea level variability is primarily correlated with the North Atlantic Oscillation (NAO). By contrast, variations in the Atlantic Multidecadal Oscillation (AMO) and the Atlantic Meridional Overturning Circulation (AMOC) seem to be linked only to lower-frequency components.

Future projections under different SSP scenarios show that sea level could rise as much as 395 mm in Santa Cruz and 365 mm in Las Palmas in 2050 under the most pessimistic emissions scenario (SSP5-8.5). An additional 20 mm could be added due to land subsidence if it remains constant. Since these projections do not fully match NASA estimates, they highlight the need for locally calibrated models that consider regional oceanographic processes and land motion.

In conclusion, the Canary Islands have a complex and dynamic sea level regime that cannot be fully understood through global averages. The influence of factors such as mesoscale processes, vertical land motion, and climatic modes could intensify local impacts, highlighting the necessity of ongoing monitoring and specific studies particularly under high-emission scenarios. Future work should further explore the role of mesoscale and seasonal processes and integrate high-resolution regional models with observational data. Enhanced long-term monitoring and localized projections will be essential for effective adaptation planning in this vulnerable region.

Annex I: List of abbreviations

Abbreviation	Meaning
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
CMEMS	Copernicus Marine Environment Monitoring Service
EA	East Atlantic Pattern
EKE	Eddy Kinetic Energy
ENSO	El Niño–Southern Oscillation
GMSL	Global Mean Sea Level
GNSS	Global Navigation Satellite System
IPCC	Intergovernmental Panel on Climate Change
LMSL	Local Mean Sea Level
LP	Las Palmas de Gran Canaria (Tide Gauge Station)
NAO	North Atlantic Oscillation
PDO	Pacific Decadal Oscillation
PSMSL	Permanent Service for Mean Sea Level
SC	Santa Cruz de Tenerife (Tide Gauge Station)
SSP	Shared Socioeconomic Pathways (IPCC Emission Scenarios)
SST	Sea Surface Temperature

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Descripción detallada de actividades desarrolladas durante la realización del TFT

Se llevó a cabo una revisión bibliográfica exhaustiva y se procedió a la descarga y recopilación de distintos conjuntos de datos, entre ellos datos altimétricos, de temperatura del mar (Copernicus) y registros de mareógrafos (PSMSL). Estos datos fueron posteriormente tratados y procesados mediante el software MATLAB, utilizando herramientas de análisis, visualización y filtrado que permitieron obtener resultados útiles para la interpretación de la estacionalidad del nivel del mar en la región de estudio.

Formación recibida (cursos, programas informáticos, etc.)

El tutor proporcionó y orientación continua en el uso de MATLAB, lo que permitió una profundización en el manejo de este. Esta formación ha sido interesante para adquirir competencias técnicas que hasta el momento no había tenido la oportunidad de desarrollar.

Nivel de integración e implicación dentro del departamento y relaciones con el personal.

La integración dentro del departamento ha sido buena, ya que ha habido una buena relación con otros investigadores. La implicación en el trabajo y la disposición a colaborar han sido positivas, generando un ambiente de trabajo muy adecuado.

Aspectos positivos y negativos más significativos relacionados con el desarrollo del TFT

Entre los aspectos positivos, destaca el descubrimiento de un campo nuevo para mí. Además, este campo parece estar aún poco desarrollado en el contexto específico de Canarias, lo que refuerza su potencial futuro. También ha sido muy enriquecedor el uso de herramientas de programación que no había utilizado anteriormente.

En contraposición, la parte más negativa de la realización del TFM han sido sin duda los plazos. Los tiempos son muy limitados para profundizar y disfrutar del proceso de aprendizaje que debería brindar un proceso como este.

Valoración personal del aprendizaje conseguido a lo largo del TFT.

El desarrollo del TFT me ha permitido cumplir con los tiempos de entrega establecidos y redactar un documento siguiendo el formato de artículo científico, lo cual ha sido un ejercicio valioso de comunicación académica. Desde el punto de vista del contenido, ha supuesto el descubrimiento de una temática novedosa para mí, con una relevancia mayor de la que inicialmente imaginaba, especialmente en relación con la planificación y adaptación ante posibles eventos extremos en una región especialmente vulnerable como es Canarias.