Sea level change in the Canary Islands

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Trabajo de fin de título presentado por Natalia Preciado Mancera
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Abstract

The speed of the increase of the sea level in the past years has been getting faster. In the case of the Canary Islands, the change in the sea level has been presented differently in the diverse islands. The methodology used was to perform a harmonic analysis in the data of the tide gauge of the Canary Ports to subtract the cycles with astronomical origin and to verify that the major tidal constituents remain the same than the one reported by Puertos del Estado, the outliers were also extracted from the data. The resulting sea level data was used to perform a linear regression analysis with local and hourly records, there was observed the behaviors of the sea level with changing intervals of time, every three months, four years and the whole period It was found that there is a similar behavior between the global and the shortest periods of time when enough data were present. In the three-month periods of time a seasonal conduct was observed between the different ports, being the sea level highest in summer and lowest in winter. Monthly and seasonal correlations were made with the North Atlantic Oscillation (NAO), obtaining negative correlations values. Additionally, there were performed a future projections for and were compered with those of Ramírez Pérez et al. (2019), obtaining different results due to the procedures used, but staying within the behavior presented in various studies as the one of Calafat et al., (2012).

Keywords

Sea level rise, NAO index, linear regression analysis, global change.

Resumen

El ritmo con el que aumenta el nivel del mar ha ido acelerando a lo largo de los años. En el caso de las islas Canarias, esto se ha ido presentando de diferente forma en las diversas islas. La metodología utilizada fue realizar un análisis armónico en los datos de los mareógrafos en los diferentes puertos de Canarias, para verificar que los constituyentes armónicos fueran similares a los reportados por Puertos del Estado, e igualmente para remover la ciclicidad presente en la serie dada por un componente, además de remover los valores atípicos. Se ejecutó un análisis de regresión lineal con registros horarios y locales ya tratados. Observando el comportamiento del nivel del mar con intervalos cada tres meses, cuatro años y del periodo completo. Se obtuvo un comportamiento similar al global en los periodos de tiempo más corto cuando se tenían los datos suficientes. En los períodos de tres meses se observó un comportamiento estacional análogo entre los diferentes puertos, siendo más alto en verano, y más bajo en invierno. Se realizaron correlaciones mensuales y estacionales con la Oscilación del Atlántico Norte (NAO), obteniendo correlaciones negativas. Asimismo, se realizaron predicciones para el año 2100 y se compararon con el modelo obtenido por Ramírez Pérez et al. (2019). obteniendo resultados diferentes por los procedimientos usados, pero manteniéndose el mismo comportamiento presentados en estudios como el de Calafat et al., (2012).

Palabras clave

Aumento del nivel mar, índice NAO, análisis de regresión lineal, cambio global

1. Introduction

Sea level is always in constant change, in the last interglacial period it had an elevation of at least 5 meters higher than the present one. This change in sea level occurred in the context of a different orbital forcing and with a higher surface temperature, averaged over several years, at least 2 ° C warmer than today (Church & Gregory, 2019). However, in recent years there has been an acceleration in sea level rise caused by global change. Scientists mainly attribute this acceleration to ocean warming, the rapidity of loss of land ice, and the net transfer of groundwater from land to sea (Konikow, 2011).

The most relevant process that affects the change in the sea level are the variations in ocean currents and their density due to the temperature and salinity of water bodies, the abnormalities in atmospheric pressure, the exchange of ice and water masses between land and ocean, the changes in the supply of fresh water to the ocean, changes in the field of gravity and vertical movements of the ocean floor associated with viscoelastic deformation, and the anthropogenic processes that influence the amount of stored water (underground, in lakes or other reservoirs) altering the hydrological cycle (Ramírez Pérez et al., 2019).

Nevertheless, the sea level change is far from being uniform at temporal and spatial scales (Fenoglio-Marc, 2001). The spatial patterns of sea level rise produced by thermal expansion are subject to strong decadal variability related to several climate modes as e.g. the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) (Lombard et al., 2005) which suggest that the distribution of the sea level trends could be non-stationary (Cazenave & Llovel, 2010). The most important and commonly studied atmospheric modes of variability in the North Atlantic is the NAO which represents a large-atmospheric circulation pattern with an important influence in the European climate, especially in winter (Iglesias et al., 2017).

The NAO is a large-scale variation of atmospheric pressure that represents one of the main factors of climate variability in the Northern Hemisphere, influencing the temperature and precipitation that is recorded throughout Europe (Tel & García, 2002). These atmosphere-related factors cause changes of a few centimeters in sea level at the annual time scale. Because the NAO affects atmospheric pressure and its gradient over the North Atlantic, it is reasonable to expect an effect of the NAO on sea level (Yan et al., 2004). Phases of the NAO are defined by higher-than-normal air pressure in one of these regions and lower-than-normal air pressure in the other. A positive NAO causes the westerly winds to blow strongly over Europe, while the peninsula is under the action of a strong anticyclone and precipitation is low, however with a negative correlation it indicates a decrease at the sea level. If the NAO is weak, the oceanic winds cross the Iberian Peninsula, leaving precipitation, and an increase at the sea level (Iglesias et al., 2017).

The increment in air temperature is also heating the ocean and when it gets warm it expands. Actually, oceans have absorbed 80 percent of the excess heat trapped by the atmosphere since 1880 (Cazenave & Llovel, 2010). Likewise, due to this increase in temperature, it has a response in ice-covered areas where it has suffered a loss in the amount of moving ice, and an increase in sea level. Warming over the next century will continue to cause sea level rise related to thermal expansion, but the dominant contribution will likely be the loss of ice from Greenland and the Antarctic continent (Leuliette & Willis, 2011).

Furthermore, as Cazenave & Llovel (2010) mention, there is an exchange through vertical and horizontal mass flows for processes such as evaporation, transpiration of vegetation, surface and underground runoff between terrestrial waters and the atmosphere, which are an integral part of the global climate system. Some human activities such as pumping groundwater out of aquifers, damming rivers to create artificial water tanks, draining wetlands, changing the physical characteristics of the land through urbanization, agriculture and deforestation, affecting the sea level by increasing or decreasing runoff.

The variability of the Atlantic Ocean at basin-scale is known to be complex in space and time (Iglesias et al., 2017). This variability in changes at sea level carries considerable uncertainty regarding the values of ascent that will occur over time and the degree of impact that will occur in various areas. In the specific case of the Canary Islands, they are mainly affected by the variability of the northeast Atlantic and the western Mediterranean, including communication between both basins (Salat et al., 2018). Furthermore, this increase is not homogeneous, which is why the central islands of Tenerife and Gran Canaria will register higher increases than the coasts of Lanzarote (Fraile Jurado et al., 2014). As its observed in the data of this study.

Sea level records contain significant interannual and decadal variability and long records are required in order to estimate reliable secular rates that will be representative of the last century (Church & Gregory, 2001). The aim of this work is to get a deeper insight about the sea level changes in the Canary Islands. With this purpose sea level data provided by Puertos del Estado have been analyzed at different intervals of time. Sea level trends an average sea level values have been computed and correlated with the NAO index. Finally, future projections for the year 2100 have been made.

2. Study zone

The Canary Islands are located in the southeast sector of the North Atlantic, approximately between 27° to 29˚N and 14˚ to 18˚W. The archipelago is made up of eight main islands, of which Gran Canaria and Tenerife occupy central positions, while Fuerteventura and Lanzarote are located around 100 km from the African coast. The depth between islands reaches up to 3,000 m (Navarro-Pérez & Barton, 2001). The total surface area of these islands is approximately 74,900 km^2 (Fig.1).

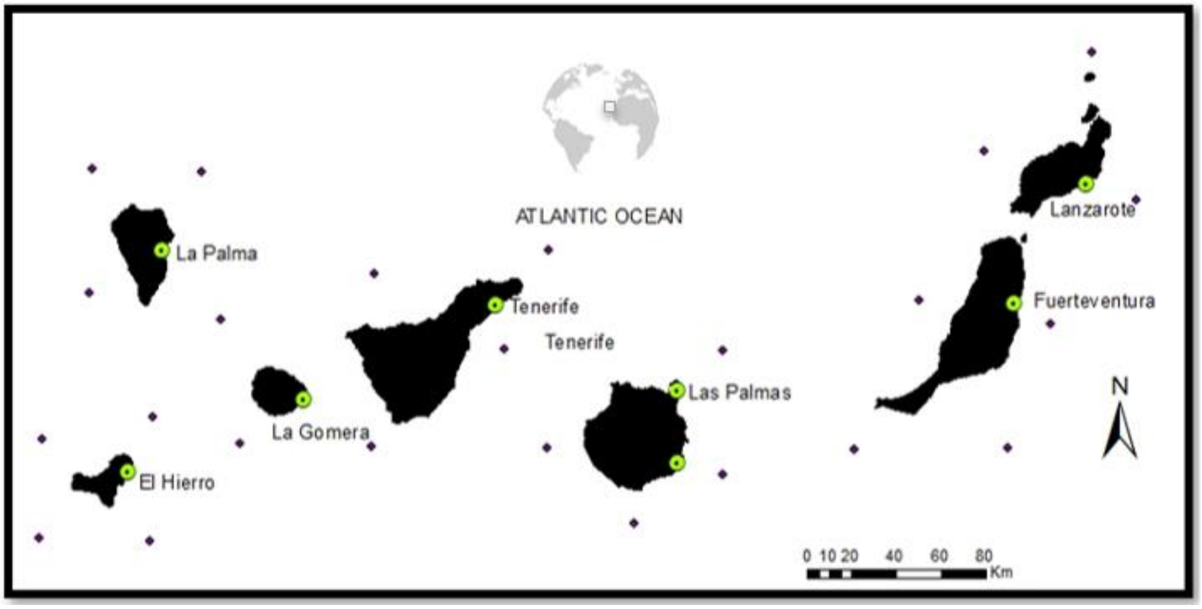


Figure 1. Map of the Canary Islands. Tide gauge represented in green. Points selected from Ramírez Pérez et al. (2019) model for comparison are presented in purple.

Fraile Jurado et al. (2014) mentions that the Canary Islands are having vertical movements, however, these changes are minimal compared to the rates of change of the mean sea level observed in the oceans, so in the case of this work is not considered as the main factor of the change of sea level.

As Petzold & Ratter (2015) states, the studies on small islands are of great interest as laboratories in terms of mitigation processes and adaptation to climate change, as well as the development of resilience to climate change, these are more vulnerable to a scenario of global warming, constituting, probably, the greatest potential threat to small islands such as the Canary Islands.

As Mendes et al. (2017) states, the tide gauge data set for the Macaronesia islands is very heterogeneous, both in terms of temporal range and completeness, resulting in a large diversity of trend estimates. Many tide gauges in the Canary Islands, for example, are part of the recently established REDMAR Spanish network resulting in time series that are too short to derive reliable trend estimates.

With the scenarios considering Representative Concentration Pathway (RCP) there is a moderate scenario (RCP4.5) and a representative scenario of high greenhouse gas emissions (RCP8.5). In both cases, a greater rise in sea level is observed on the coasts of the Canary Islands (Ramírez Pérez et al., 2019).

3. Data and methodology

Hourly sea level data from the eight ports (Fig. 1) was acquired from the available historical data of sea level from the oceanographic data bank of Red de Mareógrafos (REDMAR) network of Puertos del Estado at the following stations (Table I).

These tide gauges use measurements of the different components of sea level, including the meteorological and astronomical components. Table I illustrates the periods of time that each harbour has, dates on which this study is based on. The ports of Tenerife and Las Palmas de Gran Canaria have larger time series data than the other ports.

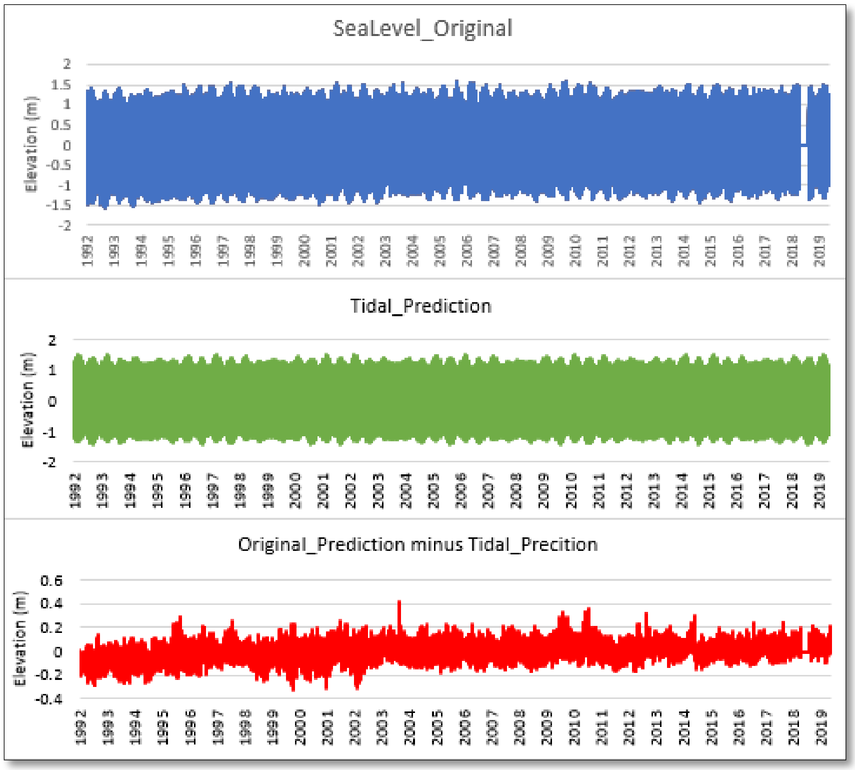
Table I. Time period, number of data and location for each one of the tide gauges.

Tide gauge	Initial date	Final date	Data number	Longitude	Latitude
Arinaga	22/02/2003	26/03/2013	79,707	13.40º W	27.85º N
Fuerteventura	01/01/2004	02/12/2019	136,380	13.86º W	28.49º N
El Hierro	01/05/2004	02/12/2019	132,569	17.90º W	27.78º N
La Gomera	01/01/2007	03/12/2019	108,766	17.11º W	28.09º N
Lanzarote	01/03/2008	02/12/2019	101,006	13.53º W	28.97º N
La Palma	01/04/2009	02/12/2019	903,12	17.77º W	28.68º N
Las Palmas	01/07/1992	02/12/2019	231,792	13.41º W	28.14º N
Tenerife	01/07/1992	02/12/2019	233,671	16.24º W	28.48º N

Hourly records were used to have a greater range of data and to have the minimum losses in the available information, these datasets have gaps of varying length (days, weeks or even months).Sea level data that were considered as outliers were deleted. Also, the values that were lower or larger than three times the standard deviation of the total time series were considered as anomalous values, therefore were removed.

After having observed the behavior of the data of Puertos del Estado, a tidal analysis was applied. Consequently, it was possible to observe the tidal amplitudes and frequencies of the major constituents, analyzing the values that were having a similar behavior than the constituents present at Puertos del Estado. Moreover, annual and semi-annual cycles with astronomical origin were removed. It was performed using T_TIDE software package in Matlab (Pawlowicz et al., 2002) (Fig. 2).

The non-cyclical component derived from T_TIDE software was analyzed by linear regression analysis to calculate the sea level change rate. This process was applied at different time scales for each tide gauge: monthly, seasonal, 4 years period and whole data period. The seasonal analysis was performed according to: winter comprising the December-January-February (DJF); spring contains the March-April-May (MAM), summer corresponds to the June-July-August (JJA) and the period of September-October-November (SON) refers to autumn. However, time periods where the number of data were lower than 50% of the total data were removed.


SeaLevel_Original

Tidal_Prediction

Original_Prediction minus Tidal_Precition

Figure 2. Original time series corresponding to Las Palmas port (blue) decomposed with T_Tide in the cyclical component (green) and the non-cyclical component (red).

The monthly time series for the NAO were extracted from the Climate Prediction Center (CPC, https://www.cpc.ncep.noaa.gov/products/precip teledoc) of the National Oceanographic and Atmospheric Administration (NOAA). Monthly sea level average was computed for each port. Therefore, using the programming language of Python were performed the monthly Pearson correlation with the NAO and each port. The average NAO index every three months (DJF, MAM, JJA, SON) was correlated with the average sea level values at every harbour.

In order to predict future local changes, it is important to use recent local trends observed by tide gauges and compare with global models or expected projections. It was performed a model to detect the change in the different islands, there was done the linear regression for each port, and calculated the rate of change. Subsequently future projection to year 2100 was obtained for each tide gauge. A spatial model was made covering the entire archipelago, with a 1 km grid, based on the sea level change trends previously obtained using Surfer 13 and ArcGIS. This model was compared with an analogous model of changes in sea level obtained by Ramírez Pérez et al. (2019). The values of the model of Ramírez Pérez et al. (2019) chosen to perform the grid (purple points) were selected in diverse zones of the islands to get more spatial information (Fig. 1).

On the other hand, following Marcos et al. (2013), sea level data recorded at Santa Cruz de Tenerife port, backed to 1927, were requested to the National Geographic Institute (IGN). Nevertheless, this information was collected from three tide gauges named TN011, TN012 and TN013. Due to the difficulties found in correlating all data to the same datum and getting the components of the tide's gauges, it was decided to discharge this data source in the present study.

4. Results

This section is divided into two parts. In subsection 4.1.1 it is observed the harmonic analysis, which compares the trend lines of the different ports, with diverse scales of time to observe the behavior of the sea level, under changing ranges of time, and correlated with the NAO index. Then in subsection 4.1.2, the future projections performed with the linear trend were modeled and compared with other models.

4.1 Spatial and temporal variation of the changes of sea level in Canary Islands

After having used the harmonic analysis (T_TIDE), it was possible to obtain the amplitude estimates of the tidal constituents for each port at Canarias Islands.

Table II. Major amplitude of tidal constituents at each harbour.

Tide	Frequency (hr)	Arinaga	Fuerteventura	El Hierro	La Gomera	Lanzarote	La Palma	Las Palmas	Tenerife
		Amplitude (mm)	Amplitude (mm)	Amplitude (mm)	Amplitude (mm)	Amplitude (mm)	Amplitude (mm)	Amplitude (mm)	Amplitude (mm)
M2	80.5	666.8	810.5	595.6	587.4	855.4	659.9	763.7	713.4
S2	83.3	267.2	305.0	241.9	233.1	316.8	254.8	290.1	272.0
N2	79.0	137.9	168.9	121.8	121.3	179.9	139.5	158.2	148.4
K2	83.6	86.9	85.0	67.3	60.6	78.7	63.9	76.7	72.1
K1	41.8	64.3	61.2	60.6	54.4	65.0	56.0	60.2	60.8

At this analysis, was compared the amplitude obtained at all the ports of Canary Islands with those reported by Puertos del Estado. The major constituents are represented at table II and displays similar values to the ones present at data base of Puertos del Estado. This show that the T_TIDE tool performs well with the data that have gaps. Therefore, the missing data for these cases have no significant effect on the estimates of amplitude of the tidal component.

The results obtained are local behaviors of mean sea level change corresponding to each port chosen for the analysis. The intervals used to perform the linear regression were the global values obtained considering all the years available for each port and every four years.

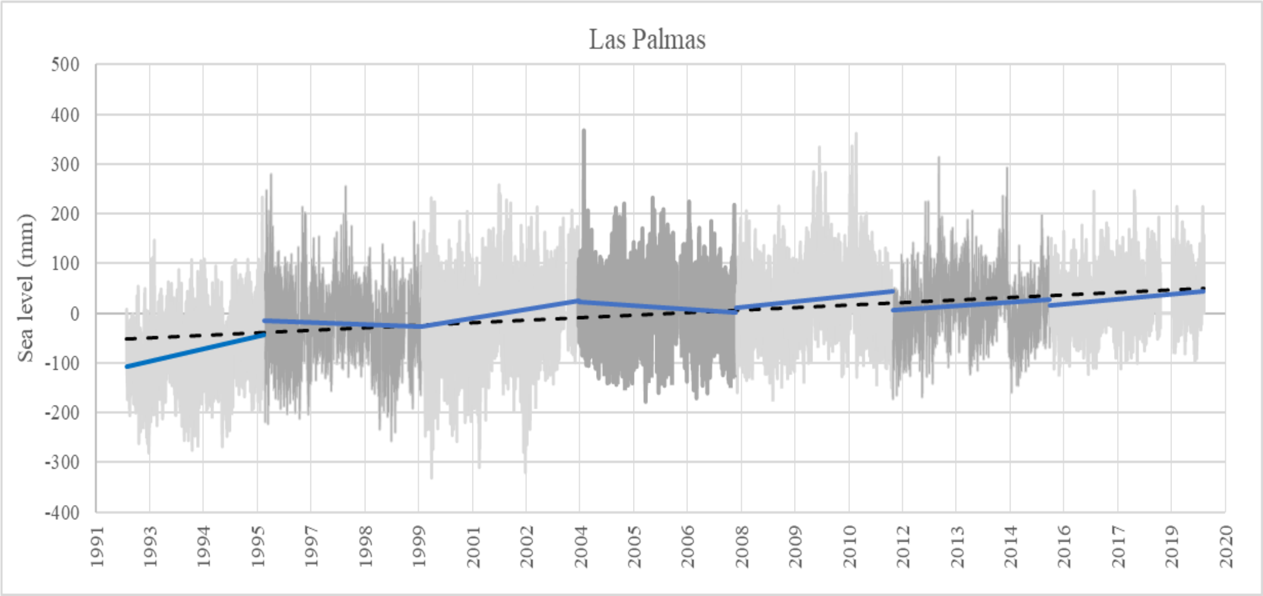


Figure 3. Daily mean sea level with the trend line every 4 years (blue) and global sea level (black).

The trend line obtained every 4 years may or may not be adjusted to the global trend line. This indicates that sea level variations are not constant over time nor do they show any apparent cyclicality at the 4-year scale considered. At table III is represented the global mean sea level at each port and the different values obtained with the period of 4 years. Knowing the number of data available for each period, it is possible to observe were the results of the trend will be more accurate. The red data represents that there were not available more that 50% of the information that should be present at the interval of time chosen, therefore was removed. All the data has been filtered to eliminate anomalous values. In all cases, the first value indicates the number of data used and the second the rate of change in sea level in that period in mm/year.

Table III. Number of data, slope of the trend line and the changing rate of sea level per year.

		Arinaga		Fuerteventura		El Hierro		La Gomera	
Puertos del Estado					2.97 ± 0.96		-1.18 ± 1.35		5.64 ± 1.65
REDMAR	**Global**	79707	5.54 ± 0.07	136380	2.59 ± 0.03	132569	-0.93 ± 0.04	108766	5.02 ± 0.05
	1992-1995								
	1996-1999								
	2000-2003	7184	78.37 ± 2.26						
	2004-2007	34073	-3.05 ± 0.23	35038	6.97 ± 0.29	29284	23.32 ± 0.32	8515	36.09 ± 1.92
	2008-2011	33599	4.94 ± 0.26	34722	-2.31 ± 0.25	34652	18.26 ± 0.27	32232	7.35 ± 0.29
	2012-2015	4851	116.32 ± 4.01	34030	4.69 ± 0.24	34707	-19.86 ± 0.27	33933	9.81 ± 0.26
	2016-2019			34368	5.80 ± 0.22	33926	5.67 ± 0.24	34086	2.06 ± 0.25

		Lanzarote		La Palma		Las Palmas		Tenerife	
Puertos del Estado			1.5 ± 1.60		0.36 ± 1.78		3.90 ± 0.04		4.28 ± 0.51
REDMAR	**Global**	101006	1.87 ± 0.05	90312	0.00 ± 0.06	231792	3.87 ± 0.02	233671	3.85 ± 0.02
	1992-1995					30244	18.23 ± 0.33	26558	18.80 ± 0.31
	1996-1999					33293	-4.07 ± 0.29	34358	-2.16 ± 0.26
	2000-2003					33555	14.41 ± 0.31	33608	14.30 ± 0.26
	2004-2007					33735	-5.09 ± 0.26	34980	3.29 ± 0.27
	2008-2011	32065	8.14 ± 0.30	23723	6.23 ± 0.53	34710	8.30 ± 0.29	35032	3.53 ± 0.29
	2012-2015	34988	4.23 ± 0.23	34822	-1.21 ± 0.26	34955	4.96 ± 0.26	34954	2.50 ± 0.26
	2016-2019	33953	3.09 ± 0.24	31767	2.92 ± 0.25	31300	10.54 ± 0.24	34181	3.84 ±0.23

From table III it is possible to observe that most of the tide gauges present positive trends in the global scale, except for the case of El Hierro and La Palmas. These global values correlate pretty well with those Puertos del Estado, also shown in same table.

Regarding the 4 years periods, most rates are positive in all harbours, which indicates that general pattern is an increase in sea level. The higher rates were present at the port of Arinaga, La Gomera, Las Palmas and Tenerife. However, the ports of Arinaga and La Gomera, have a smaller number of data that can influence the values obtained at the global rate.

In the case of the shorter studied period, the results of the intervals after having done the linear regression every 3 months, show the behavior of the sea level at the different seasons of the year at the different ports. In most of the stations it is observed that in winter (DJF), is the lowest value meanwhile at summer (JJA) the highest value is present.

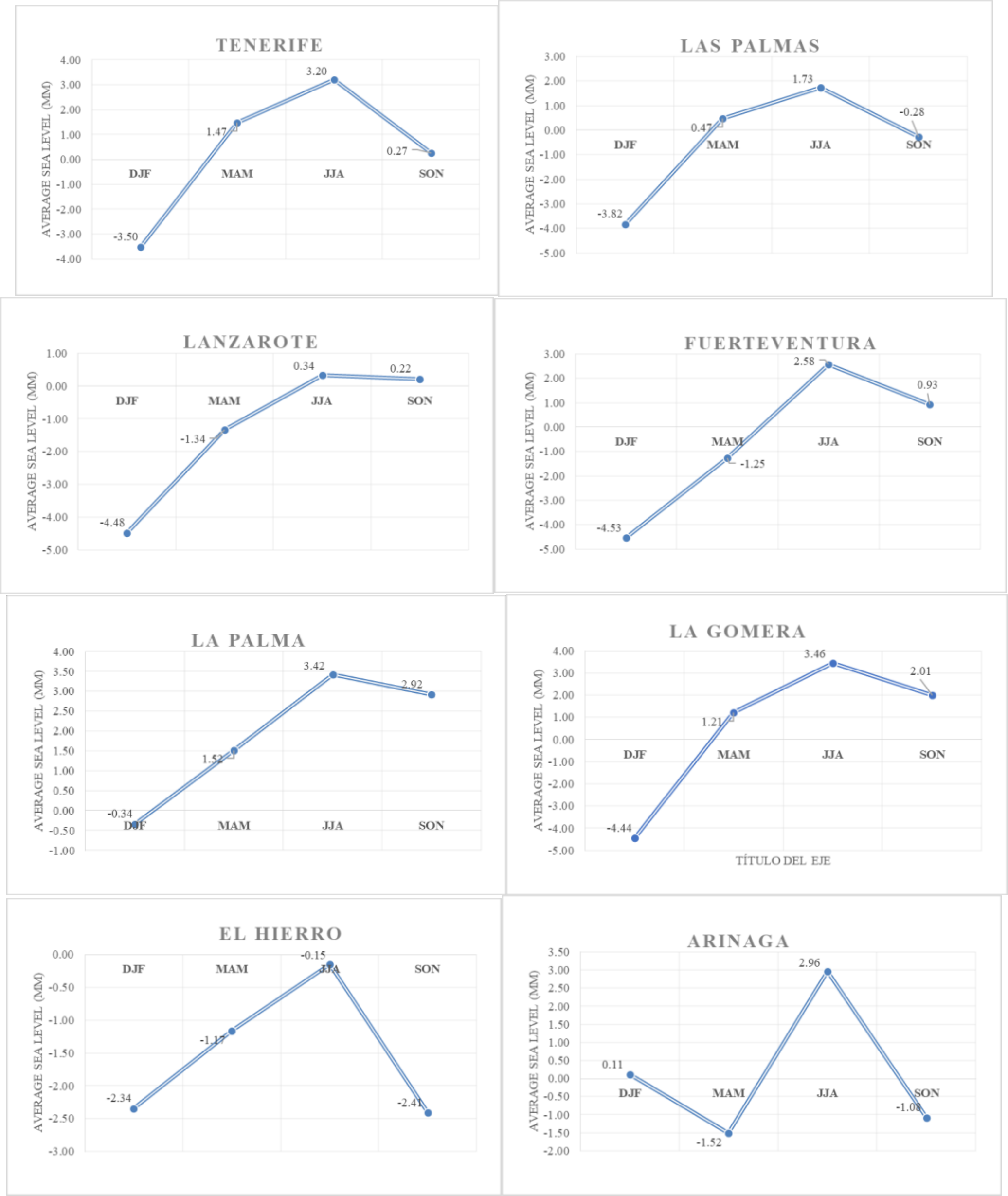


Figure 4. Seasonal variability of mean sea level at each harbour.

In figure 4 at two ports is not observed the same pattern as majority. In El Hierro and Arinaga, it's detected a different behavior, just coincided having the highest value at summer, but at El Hierro the lowest value is in autumn instead than in winter like the other ports, however, in spring and summer its observed the same tendency than the others. At the case of Arinaga the difference is that the value in spring is lower than the winter value and also in autumn is presented a low result too.

The correlation made with the NAO index and the ports were performed with monthly and seasonal data.

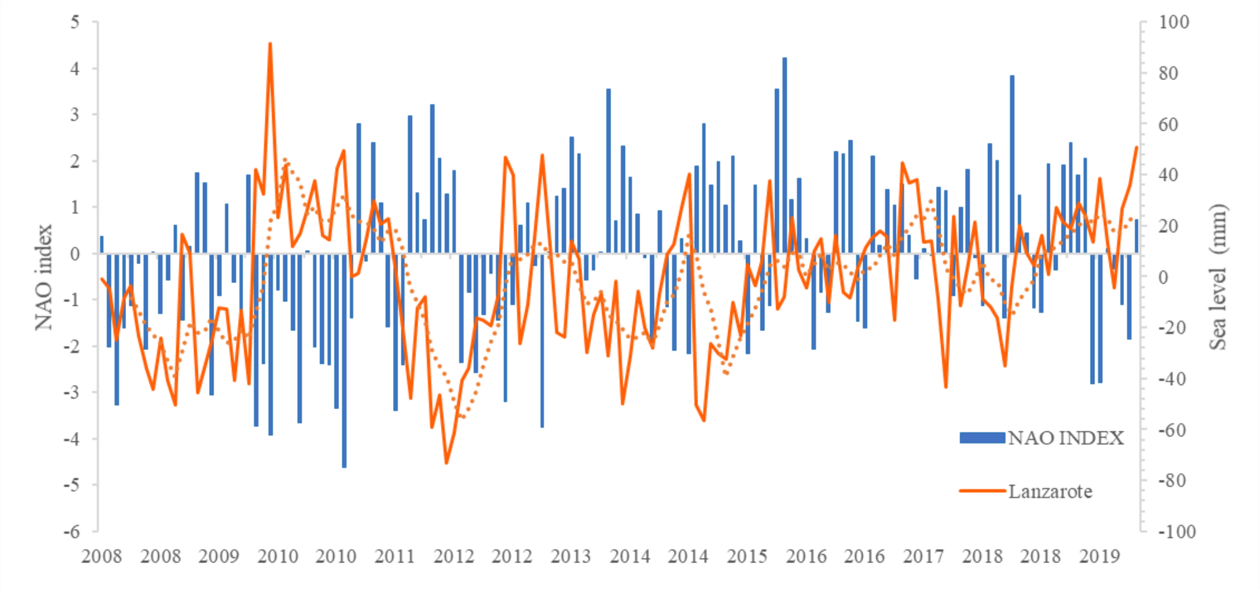


Figure 5. Behavior of monthly data of Lanzarote and the NAO index, and the rolling average for Lanzarote (dotted line).

In order to check if sea level changes are related to the NAO index, a Pearson correlation has been performed using average seasonal values of sea level and NAO index. Major values take place at wintertime but showing negative correlation. These results indicate that winter sea level is under the influence of NAO index (Table IV and Fig. 6).

Table IV. Number of data and rate of the sea level change per four-years period

	Lanzarote	**Fuerteventura**	**Las Palmas**	**Arinaga**	**Tenerife**	**La Gomera**	**La Palma**	**El Hierro**
DJF	-0.62	-0.50	-0.50	-0.80	-0.51	-0.49	-0.75	-0.73
MAM	-0.19	-0.03	-0.05	-0.24	-0.18	0.31	0.06	-0.34
JJA	0.06	0.21	-0.01	-0.37	-0.05	-0.13	0.03	-0.27
SON	-0.58	-0.45	-0.06	-0.38	-0.06	-0.14	-0.40	-0.26

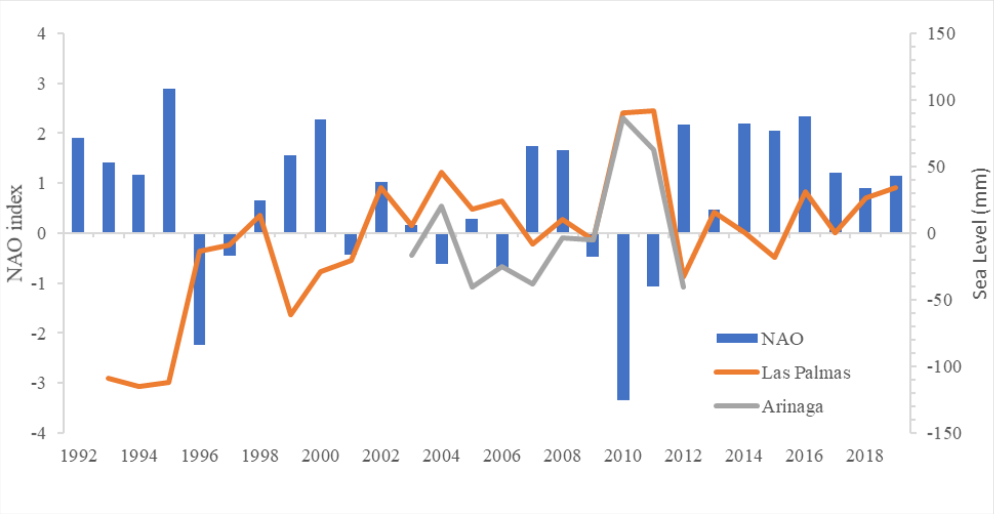


Figure 6. Behavior of NAO index and sea level measured at Las Palmas and Arinaga during the winter periods of every year.

4.2 Future projections and adjustment with spatial interpolation models

The trend line minimizes the sum of squared deviations from the data, measured in the vertical direction. Once obtained the change of sea level rate at the different harbours, future projection to the year 2100 has been performed by linear extrapolation of the obtained rates. Therefore, the values are related to sea level variations relative to the year 2020. It is important to consider that the linear extrapolation assumes that sea level change at each individual harbour will follow at the same rates as it has been recorded in the previous decades.

Table V. Sea level rate and 2100 projection for the different harbours.

	Arinaga	Fuerteventura	El Hierro	La Gomera	Lanzarote	La Palma	Las Palmas	Tenerife
Sea level rate (mm/y)	5.54 ± 0.07	2.59 ± 0.03	-0.93 ± 0.04	5.02 ± 0.05	1.87 ± 0.05	0.00 ± 0.06	3.87 ± 0.02	3.85 ± 0.02
2100 projection (mm)	443.2	207.2	-74.4	401.6	149.6	0	309.6	308

Considering all the values obtained with the tidegauges shown in table V, at the archipelago there is obtained an average sea level rise of 2.73 mm/year, which leads to 2100 projection of 218 mm. Nevertheless, this rise will not be homogeneous for the different islands, ranging from -74.4 mm at El Hierro to 443.2 mm in Arinaga.

From the 2100 projections an interpolation model has been carried out to visualize the spatial differences between each island. This model has been compared with that of Ramírez Pérez et al. (2019) (Fig. 7).

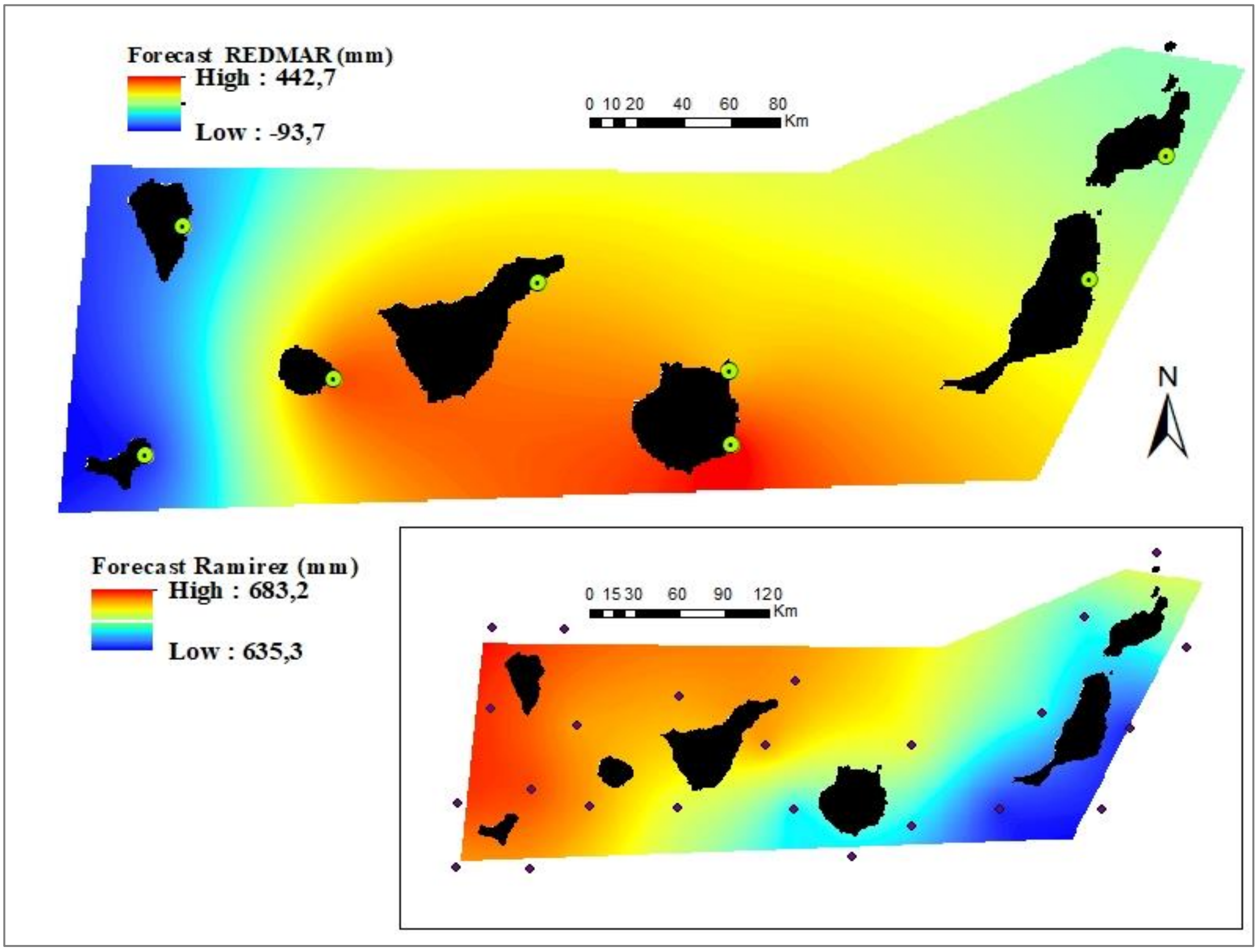


Figure 7. 2100 projections: upper image shows the one performed with processed REDMAR data, the position of the tide gauges in green. Lower imagen is the model performed with the information of Ramírez Pérez et al. (2019), purple points are the ones selected.

It is possible to observe at the images that the projections of the models are different, the model performed with the data processed of REDMAR is visible a greater growth in the central area of the islands, while towards the west and east parts of the archipelago are lower values, having the lowest value in the west (El Hierro). Contrary to what happens with the

Ramírez Pérez et al. (2019) model, where the highest value is in the west zone descending towards the East. Besides, the range of values differ, having a range of 442.7 to -93.7 mm for our model, meanwhile there is a higher maximum value for the other model with a range of 683.24 to 635.30 mm.

5. Discussion

Although it is evident that the greater the number of records, the higher the quality and precision of the analysis performed, it is essential to highlight the independence of the method developed in the face of the scarce space-time continuity of the series, which ends up becoming a notable limitation compared to most alternative statistical methods, such as the comparison of local and global trends (Fraile Jurado et al., 2014). This study has poor space-time continuity, since the data provided by Puertos del Estado only includes the eight tide gauges located at different harbours of the islands. These data series are normally quite short, since most of them only cover a 15 years period, except those of Las Palmas and Tenerife which are back to 1992.

The trends obtained are the result of many factors with variations at different time scales such as the movements of the Earth's crust, the adjustment isostatic glacier, local marine winds or variation in the density of seawater, etc. (Ramírez Pérez et al., 2019). Therefore, normally there are several factors that will affect the interpretation of local trends, depending on the aspects that were considered, and the variation of the result obtained. A linear positive trend of 2.61 mm/y was obtained by Iglesias et al. (2017) for the North Atlantic Region, which perfectly fits with the average value obtained in this work of 2.73 mm/y. Nevertheless, this behavior is far from being uniform. The results are affected by local changes as it is seen in this work. Even though the Canary Islands are in the same region, the behavior in the trend lines differ between them, giving values that range between -0.93 ± 0.04 mm/y and 5.54 ± 0.07 mm/y. The strong regional variability in sea level, have been shown by several studies, declaring that nonuniform ocean warming, hence nonuniform thermal expansion, is an important responsible for the observed spatial trend patterns in sea level (Lombard et al., 2005). As it was shown in figure 4 the lowest and highest sea level values are recorded at winter and summer respectively, which could be related to the general temperature of the ocean in the study area.

There is possible to observe a seasonal effect at the sea level behavior. At the stations of Las Palmas, Tenerife, Fuerteventura, La Gomera, La Palma and Lanzarote was normally observed that in summer were obtained the highest values, meanwhile at winter were the lowest. In both hemispheres the oceans warm and expand in summer, and contract and cool in winter (Carral, 2016; Navarro-Pérez & Barton, 2014).

The stations of the Canary Islands show the sea level annual cycles phase locked with the steric anomaly cycles, although amplitudes differ significantly from one station to the other. This fact could be interpreted as the local response to large-scale seasonal fluctuations of the Canary current (García-Lafuente et al., 2004). Therefore, having an impact in the sea level present at different stations, due to the locations of the island and the season of the year, as is observed in the data of this study, were the values are different with the divers locations.

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Either the four-year period as well as the seasonal study show that sea level rates are not constant on time. In order to explain this variability, the NAO index has been used. The Pearson correlation between the NAO index and seasonal sea level at the different harbours shows a clear negative correlation in winter (Table IV), which coincide with the argument of Woolf et al. (2003) who states that Sea level is generally lower in NAO Positive winters around the Azores and in southern Europe. This indicates that the sea level on the coast responds to barometric variations in the Island. “Southern Europe appears to have a negative sensitivity to NAO index. The negative response to the NAO can be attributed – at least in part – to both the southern node of the pressure dipole and to the effect of NAO on surface fluxes” (Woolf et al., 2003) being the possible reason to the response of the change of the sea level due to the NAO. For comparison propose was observed the correlation value obtained for Marcos et al. (2013) for Tenerife and the winter NAO index with a value of -0.56, similar to the one obtained for this study.

The lowest NAO index value recorded during our study period took place in the winter of 2100 coincides with the peak of positive sea level in that year at the stations at Canary Island while the positive NAO index in 2012 would be in agreement with the lower mean sea levels the same year (Pérez-Gómez et al., 2015), as can be seen in figure 6.

Yan et al. (2004) mention the NAO effect may arise for three reasons. Firstly, the NAO-related large-scale changes in the atmospheric pressure field over the North Atlantic will force sea level changes. Secondly, the NAO-related pressure gradient anomalies determining the wind field over the North Atlantic will result in circulation and storm surge changes, and thus cause sea level changes. Thirdly, changes in the heat exchanges linked with the large-scale meteorological variability may result in steric sea level changes. However, it remains unclear at which time scales the different mechanisms play the most important role in driving sea level changes. "The scales of these phenomena vary from years to decades, even scales of up to a century have been described for the NAO" (Tel & García, 2002). Subsequently, the results of current study must be considered in the measure of the partial information that these series can provide. Probably due to the different scale of this phenomena, the monthly values confer lower values, showing just the negative correlations but not being significant values for this study.

For the comparison with the model of Ramírez Pérez et al. (2019) the rise in mean sea level for the Canary Islands at the end of the century ranges from 710 mm to 908 mm. The ascent is higher in the Canary Islands than in the rest of Spain. Specifically, the maximum rise in mean sea level is expected to the west of the island of La Palma. Meanwhile at this study was obtained lower values that range between 443.2 mm at Arinaga to -74.4 mm at El Hierro, were the increase was more significant at the central part of the archipelago, and going lower to the eastern and western boundaries, having the smallest value at El Hierro and La Palma, contrary to Ramírez Pérez et al. (2019).

These differences between both models could be due to that Ramírez Pérez et al. (2019) used altimetry measurements, had more data spread over a greater area to extrapolate the model and longest time series. However, as Carral (2016) states, the altimetry systems often show problems in coastal regions, where altimeter measurements have less precision and find it more difficult to interpret the data. These drawbacks are mainly due to contamination of the radar signal due to the proximity of the coast, inaccuracies in the tidal corrections and the delay in the propagation of altimetry signals due to the humid component of the troposphere. Added to these problems is the complexity of coastal zones, regions with a wide range of hydrodynamic processes with different spatio-temporal scales. Consequently, granting other factor to present different values than the ones obtained with the tide gauges. Although the result obtained by the data processed of REDMAR are closer to the one presented by Fraile Jurado et al., (2014) were he mention that the central islands of Tenerife and Gran Canaria will register higher sea level rises than the coast of Lanzarote.

As well, it is possible to observe different results in the bibliography. At the case of Tenerife, at this study was got the result of 3.85 ± 0.02 mm/y obtained with the information processed from REDMAR. This value is a higher value than other values as the one found by Marcos et al. (2013), where the observed sea level rise at Tenerife was 2.09 ±0.04 mm/y for the period of 1927-2010. Moreover, this value is larger than the (geocentric) global average for the 20th century estimated by Church & White (2011), with a value 1.7 mm/y, or by Tel & García (2002) giving a value of 0.8 mm/y for the Canary Islands. Likewise Mendes et al. (2017) mention that the relative sea level trends for a selected number of tide gauges in Macaronesia exhibit large dispersion, ranging from −1.1 mm/y at La Palma to 5.1 mm/yr at Tenerife. Therefore, there are reported different values as local, around the islands, towards the Macaronesia Islands, and global as the Atlantic. Showing that is normal to obtain different values either in the same study or between different ones.

As Marcos et al. (2013) describe that besides the barotropic response of local atmospheric pressure and winds, it is proved that coastal sea level variations on the eastern boundary of the North Atlantic northward of about 25°N display a baroclinic response to longshore winds. In essence, when the wind blows parallel to the coast with the coast on its left it displaces surface water offshore through Ekman transport. Because there can be no flow normal to the coast, the displaced surface water needs to be replaced by denser water from deeper levels, which pushes the thermocline upward and thus results in a decrease in the steric sea level. Factor that could be affecting in the results obtained at the current study where the eastern part of the island (Fuerteventura and Lanzarote) have lower values than the central ones.

6. Conclusions

Statistical analysis allows us to verify that the phenomenon of the rise in mean sea level shows spatial differences that must be considered. As Mendes et al. (2017) mentions, these large differences between stations, that sometimes are relatively close, could be due to undetected measurement errors at some stations, local movement or/and mesoscale activity. This gives different results in diverse parameters, depending on the location of the islands, according to whether they were further west or east, as it is show in the results.

The sea level records comprehend significant interannual and decadal variability affected by a lot of factors and long records are required in order to estimate reliable secular rates that will be representative. Sea level variability can be depicted in terms of its response to the main atmospheric modes, representing some of the complex interactions between the oceanic and atmospheric systems (Iglesias et al., 2017). The number of records present in this study could be affecting our results, as it could be see with the tide gauge that had less information as Arinaga behave more different than the others.

After having performed the monthly correlation with the NAO index and the data, were found not significant negative correlation values, nevertheless all the ports present the same negative pattern, showing that sea level atthe Canary Islands have an opposite behavior with the NAO index. However, due to the low values obtained, it is considered that the monthly sea level behavior cannot be explain by the NAO index, other factors have a higher impact on the change of the sea level. Tel & García (2002), mentions that the correlation between mean sea level is higher for atmospheric pressure than for the NAO index, showing that there could be another factors that influence more the variation in the change of monthly coastal sea level and that keeps the local signals in addition to the regional behavior.

The seasonal behavior presented at the different tide gauges confirms a higher sea level value in summer and lower in winter. The higher negative values of correlation were presented at winter, therefore, this results of the behavior of the sea level during winter could be explain by the NAO index: when it is in the positive phase, the sea level is lower, and when it is at the negative phase there is present a higher value of the sea level, having more influence during winter.

Performing a linear model offers a quick overview of the sea level rise and can be used for illustrative purposes, as perceived in the forecast of the sea level increase in different areas and different periods. From the interpolation model carried out for 2100 scenario, it is possible to observe a general increase of the sea level, getting higher values in the central parts of the archipelago as Arinaga with a value of 443.2 mm, La Gomera with 401.6 mm and Las Palmas and Tenerife with 309.6 mm and 308 mm respectively. Meanwhile, having smaller values at the western part of the archipelago, with La Palma having 0 mm and El Hierro with -74.4 mm. At the eastern part of the archipielago, could be also observed that the farthest the island is from the central part the lowest the value is. Fuerteventura have a value of 207.2 mm and Lanzarote 149.6 mm.

Concluding that there is observed and general increase of the sea level, with a similar behavior as the one presented by Fraile Jurado et al. (2014) were he indicate that the central islands of Tenerife and Gran Canarias will register higher increases. But due to the short data series and all the factors related to the sea level rise, more studies should be performed, considering more parameters, longer data series and additional data sources such as altimetry to better understand the results obtained with the movement of the sea level along different zones.

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