Sea level variability along the Spanish Coast, 1990-1999

María-Jesús García [1], Begoña Pérez [2], María-Angeles Fraile [3], José G. Millan [4]

[1] Area de Medio Marino, Instituto Español de Oceanografía, Spain
[2] Clima Marítimo, Puertos del Estado-CEDEX, Spain
[3] Servicio de Geodesia, Instituto Geográfico Nacional, Spain
[4] Sección de Oceanografía, Instituto Hidrográfico de la Marina, Spain

Sea level is monitored in Spain by various agencies for different applications: control of the national levelling system, oceanographic studies, climate change, operational purpose, harbour operations, navigation, etc. A general overview of the Spanish sea level networks is presented in this paper, as well as the new strategy that is being discussed for the ongoing sea level monitoring system in Spain. The sea level data for the period 1990-1999 is examined and general information about the mean sea level evolution during that decade. Seasonal variability and tides are presented.

1.Spanish Sea level Networks Overview

In 1870 the first tide gauge was stabilized in Alicante (Spain) by the Instituto Geográfico National (IGN) in order to determine the mean sea level of Alicante as a reference of the National Leveling Network. A few more gauges were installed along the coast for the primary leveling network. In 1943 the Instituto Español the Oceanografía (IEO) established a large network for oceanographic studies and navigation purposes. Finally, in 1989 the old Dirección General de Puertos, decided to create a permanent sea level monitoring system for operational purpose and harbor operations. Recently some more tide gauges are being installed by the Instituto Hidrográfico de la Marina (IHM) for hydrographic studies. The stations included in figure 1 compose the actual network.

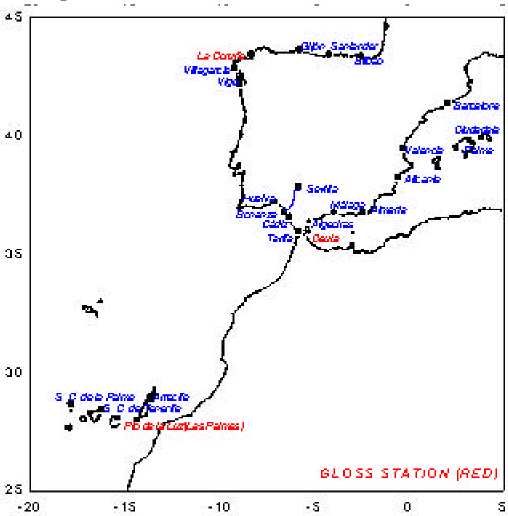


Figure 1. Stations of the Spanish sea level network

The measurement equipment systems installed in the stations are basically of two types: stilling well float gauge and acoustic gauges. There are only a few stations with a pressure system. Nowadays, in all the stations, in addition to the graphical output, there is a digital output system with radio or modem transmission. Therefore, the data are available in near real time. In some of the station there are installed oceanographic and atmospheric parameter sensors too, mainly sea temperature, air temperature and barometric pressure. All these parameters are clearly an important source of information for a better knowledge of the long-term mean sea level in each station and its evolution.

But to determine the temporal and spatial mean sea level changes, the sea level measurements are related to the tide gauge benchmark (TGBM), on his part, is linked to the Geodetic National Leveling. Auxiliary BMs close to each TGBM are levelling from time to time to register the vertical land stability in order to obtain the absolute sea level measurements. During the last decade, in the course of various campaigns, the TGBM of some stations have been refereed to a global reference system. As a result of the 1998 compensation leveling, carry out by the Instituto Geográfico National, a much better knowledge of the mean sea level variation along the peninsular coast is presented in figure 2, in which it can be seen that the latitudinal slope of the mean sea level is 2.99 cm per degree of latitude.

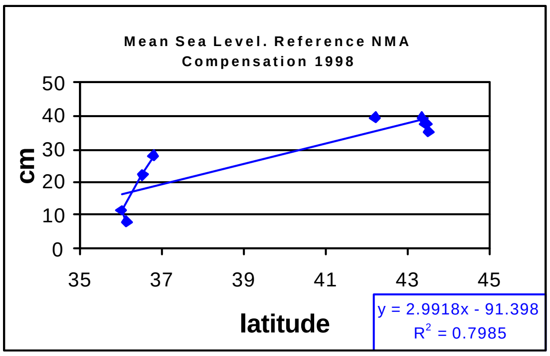


Figure 2: Latitudinal slope of the mean sea level.

Another important result has been obtained from the global reference in the two coast of the strait of Gibraltar. The Real Observatorio de la Armada (ROA) is carrying out this research. One result is that the mean sea level of the station in Ceuta (African coast) with those in Tarifa, Algeciras y Cádiz (European coast) can be compared as it is shown in table 1.

Station	MSL over TGZ	Altitude of TGZ Related to WGS-84
Cádiz	2.035 meters	43.197 meters
Tarifa	1.090 meters	40.492 meters
Algeciras	0.76 meters	41.713 meters
Ceuta	.887 meters	41.314 meters

Table 1. Mean sea level (1990-1999) over TGZ.
Altitude: TGZ related to WGS-84 (ROA).

Concerning to the chart datum, the Instituto Hidrografico de la Marina (IHM), is recalculating the hidrographic zero at each stations using the new protocols established by the Bureau Hydrographic (BHO).

2. Strategy

Over the last years, with the use of the new technologies, new type of system measurement equipment has been developed. The Spanish network is using a modern system: Acoustic gauges. Also, for the traditional float, an encoder and a data logger with data modem transmission facility has been incorporated, but also a tide gauge with radar technology is being testing.

But the most important advance for the sea level monitoring is the modern geodetic techniques for geodetic fixing of the tide gauge bench mark. With this technique it will be possible not only to calculate the absolute sea level by removing the crustal movement but also to refer the sea level measurement to a global reference system. Then the tide gauge sea level data can be comparable with the altimetry data and therefore a better knowledge of the spatial variation will be obtain. In Spain, as mention before, this technology is being used in many stations. The strategy for the future is to select some station for sea level long-term evolution. In those stations a permanent GPS will be install. At each of other stations, an annual or biannual GPS campaign will be carry out.

Concerning to the data analysis, a preliminary trend of the relative monthly mean sea level time series are presented in figure 3.

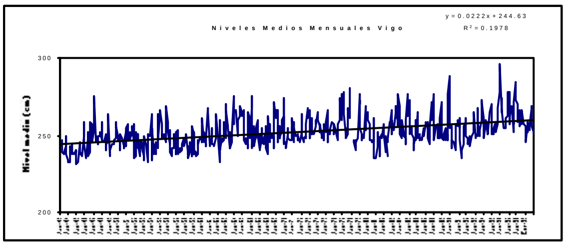


Figure 3. Vigo Mean Sea Level Evolution

But in the future, applying a mathematical model to the monthly mean sea levels in order to remove the meteorological effects will be perform the determination of the long-term mean sea level and its evolution. The method, as described in (Pugh, 1987), consists of fitting a mathematical function to the time series of $Z_0(t)$ by a least square technique. The analytical expression to include in the model is:

$Zo(t)= \check{Z}\ o(t)+ at$ (long-term mean and trend)
$+ N+ S_{a+}\ S_{aa}$ (periodic tidal terms)
$+\ b_0P_A+b_1\ \ P_A\backslash\ \ x+b_2\ \ P_A\backslash\ \ y$ (meteorological effects)

3. Data processing

The sea level is measured in 1, 5 or 10 minute's intervals. It varies in function of the different purposes. For example to study the seiches that appears frencuently in Palma de Mallorca, the data are registering every minute. The raw data are transmitted to the Data Center and a quality control procedure is performed to eliminate obvious errors as clears spikes, date and changes in references.

Then, clean data are filtered to obtain the hourly data. The two filters mainly used are the 54 points symmetrical filter (Pugh,1997) and the consecutive mobile means $A_mA_mA_n$ (Godin,1972). The results of these two filters are different and when the Godin filter is used the lost energy should be recover at harmonic analysis step.

The hourly data are processing with the software developed by the University of Hawaii Sea level Center (Caldwell, 1998) to perform; harmonic analysis and prediction (Foreman, 1997), hourly quality control by inspection of the residual, and, the daily mean values by removing the diurnal and semidiurnal tidal constant.

The monthly and annual mean sea level is calculated by a simple weight mean. The tidal ranges are calculated on an annual basis.

4. Annual Mean Sea Level Evolution.

In this paper, the values obtained for the mean sea level are the relative mean sea level in which there are included not only the crustal vertical movement but also the meteorological effects. The information about the crustal movements is very poor. In fact the results presented by (Emery & Aubry, 1991) are based in the relative mean sea level trends.

The annual mean sea level evolution during the decade (1990-1999) shows in figure 4 an increase sea level from 1992 to 1997. This year presents the higher level in almost all of the station. But also it can be seen that in the Sevilla-exclusa station, located in the river Guadalquivir, the extremely high level of this year give an idea of the large impact of the storms. As a complementary information, in the pacific the sea level rise 25 cm as the impact of the Niño 1997. In Spain during the decade 1980-1999 (Lavin&García ,1992) the highest mean sea level occurs in 1983 and 1987, the same years as the Niño 1982-1983 and 1987.

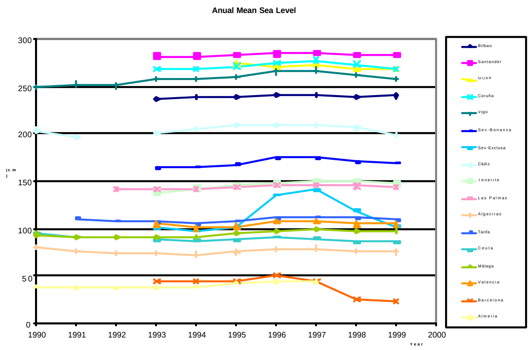


Figure 4. Anual mean sea level.

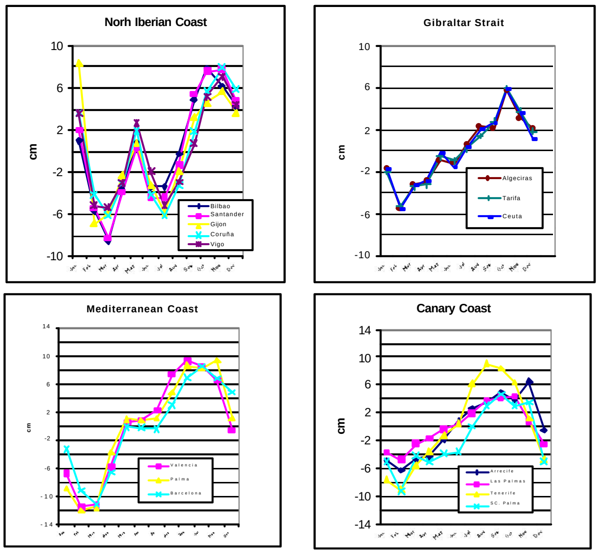
5. Seasonal variability.

The seasonal variability has a close relation with the wind and atmospheric pressure. Then, as the monthly data are not removed from this effect, a marked seasonally in monthly average appears. The behavior of the seasonal variability is presented in figure 5a-5d the results are grouped in regions according to the climatology of each region. In the Iberian Peninsular Coast the seasonal variability shows a clear decrease of sea level in the summer time, and an increase in the autumn season. Lowest values occurs in July or august and higher in October or November. The range is about 16 cm. (Lavin & García, 1992) and has been found a clear relation of this variability with the atmospheric pressure, high barometric factors, and also with the wind stress.

The seasonal variability in the Strait of Gibraltar and in the Mediterranean shows a gradual increase in the sea level between February and October. Then it begins to decreases until February. The ranges are about 12 in the Gibraltar Strait and about 22 in the Levantine Coast. The main causes of this observer variability are the atmospheric pressure, the wind and the volume thermal expansion. In summer the atmospheric pressure is fairly low in this region (less than 1020 mb). On the other hand, in this area the wind blows during the summer from East to West. So the East wind flowing in the summer months piles up the water in the Spanish Mediterranean coast. Furdermore the sea temperature is rather warmer in summer than in winter (Medatlas climatology, 1996).

The seasonal variability in Canary Island presents its minimum in February and the maximum appears in August or September instead of October-November. The rage of the variability is around 10 cm in all the stations except in Tenerife (20 cm). Part of the progressive sea level increase between June and August could be explained by the onset of the trade winds, which piles up the water in the eastern of the island. ISEMER and Hasse (1987) shows highest trade winds stress forces during the summer, about .12N/m^2, twice the January value. The seasonal variability in S.C de la Palma and in Arrecife have been calculated taking into account the last 2-3 last years. For this reason, the pick that appears in November could be due to a particular behavior of the sea level during those years.

a) Norh Iberian Coast b) Strait of Gibraltar



c) Mediterranean Coast d) Canary Island

Figure 5. Seasonal Variability.

6. Tides

The Harmonic analysis (Foreman 1977) has been applied to the hourly data for periods of 366 days to obtain the main constituents. The semidiurnal contituents are dominant (From Factor < .25) in all the atlantic coast. In the Mediterranean Coast, Malaga has also a semidiurnal tide but it is close to a mixed tide (form factor = 0.21) but Valencia presents a mixed tide, mainly diurnal (Factor Form=2.67) and became mainly semidiurnal in Barcelona (Factor Form = 0.67).

The mean values of the M2 and its standard deviations have been obtained using the years, within the decade, that have enough data and quality, to perform the harmonic analysis. The standard deviations of the amplitudes are less than 0.2 cm, larger in Coruña and Cádiz. The standard deviations of the phase are about 0.5 (g) and much large in some stations about 1.1(g), but probably, is because of some time error on the data. In the figure 8 the amplitude and phase of the M2 constituent shows its propagation along the coast from south to north in the Atlantic coast coast.

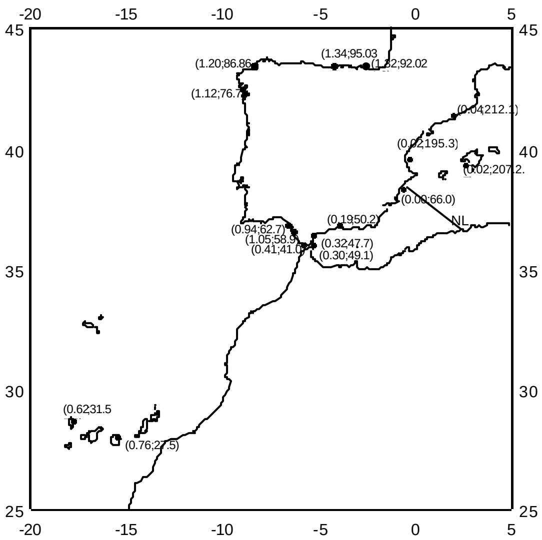


Figure 8: M2. Amplitude and Phase

The Strait of Gibraltar is a very complex area and more gauges would be necesary to describe with detail the progagation of the tide in this region. A very complete description can be found in Garcia Lafuente (1996), who used a network composed of 4 temporary pressure gauges at each side of the strait. One of the most important features is that the M2 amplitude increase from East to West along the strait. In the figure 2 , it can be seen that the amplitude of tarifa is 9 cms higher than in Algeciras.

In the Mediterranean Coast, the amplitude of M2 is increasing from Alicante to Algeciras and in the opossity direction from Alicante to Barcelona, and the big jump of the phase between Alicante and Valencia shows the existence of the well known Alicante–Oran nodal line.

The maximum and minimum tidal ranges found for de decade is presented in table 2. that shows that the tides in the Mediterranean are very small and in the Atlantic the maximum ranges decreases from north to South and there are a big differences in the spring tides and neap tides

Station	Tide range (cm)		Station	Tide range (cm)	
	Max	Min		Max	Min
Bilbao	503	117	Ceuta	119	18
Santander	501	118	Algeciras	122	16
Coruña	458	103	Málaga	84	9
Vigo	421	99	P. Mallorca	23	0
Bonanza	347	82	Las Palmas	297	50
Cádiz	407	76	S.C. de la Palma	244	44
Tarifa	163	26			

Table 2. Maximun and minimun tide ranges.

Conclusion:

The sea level is monitoring in Spain taking into account the new technology not only in the measurement equipment system but also in the geodetic fixing. This way of research will improve to understand the long-tem evolution of the mean sea level and the spatial variation.

The annual mean sea level evolution during the decade shows the higher level in 1997 in all the stations and also appears an increasing trend from 1992 to 1997. However, this result seems to be influence by the climatological cycles. Anyway the determination of the means sea level and the long-term trend need to be performed by removing the atmospheric influence.

The seasonal variability is higher in the Mediterranean (22cm) that in the Atlantic (10cm-12cm) with the exception of Tenerife.

The tides ranges are very low in the Spanish Mediterranean Coast.

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