DATA PAPER

Historical tide gauge sea-level observations in Alicante and Santander (Spain) since the 19th century

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Abstract
A set of historical tide gauge sea-level records from two locations in Santander (Northern Spain) and Alicante (Spanish Mediterranean coast) have been recovered from logbooks stored in national archives. Sea-level measurements have been digitized, quality-controlled and merged into three consistent sea-level time series (two in Alicante and one in Santander) using high-precision levelling information. The historical sea-level record in Santander consists of a daily time series spanning the period 1876-1924 and it is further connected to the record from the modern tide gauge station nearby, ensuring datum continuity up to the present. The sea-level recording in Alicante started in 1870, with daily averaged values until the 1920s and hourly afterwards, and the tide gauges at the two Alicante sites are still operating, thereby providing one of the longest tide gauge sea-level time series in the Mediterranean.

Dataset
This dataset contains historical sea-level information at Alicante (Western Mediterranean), since 1870, and Santander (Bay of Biscay), since 1876. It consists of three sea-level records (two in Alicante and one in Santander) that have been recovered and digitized from logbooks and merged into consistent time series using high-precision levelling surveys, with temporal resolution between hourly and daily. The sea-level records are distributed by the British Oceanographic Data Centre.

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INTRODUCTION

Sea-level observations are among the longest environmental records due to their relevance for maritime navigation and harbour operation (Pugh and Woodworth, 2014). Some instrumental tide gauge measurements date back to the 18th century, although it took until the mid-20th century before the tide gauge network was truly global and covered most of the world's coastlines (Holgate et al., 2013). However, few century-long sea-level time series are currently available before 1900. This scarcity of long-term sea-level observations, as well as their uneven geographical distribution, is a major challenge for climate studies that address, for example, the quantification of mean sea-level rise at centennial time scales, the accurate assessment of sea-level acceleration or the long-term changes in sea-level extremes that are vital for coastal risk assessments (Holgate et al., 2013).

In this context, sea-level data archaeology, understood as the discovery, recovery (through digitization of paper-based observations), quality control, and publication of historical observations from archives, is an essential contribution to climate research. The Global Sea Level Observing System (GLOSS) has recognized its relevance in different fields of oceanography and has contributed to the recovery of historical sea-level data since 2013 (Bradshaw et al., 2015).

A number of recent efforts have aimed to increase the number and length of sea-level time series. Hogarth (2014) extended the Permanent Service for Mean Sea Level (PSMSL) tide gauge database using historical information, adding a total of 4,800 station-years, including many non-standardized observations that were already public. Likewise, Talke and Jay (2017) identified more than 6500 station-years along the North American coasts; digitization efforts are ongoing. Other investigations have focused on particular sites. A non-comprehensive list of recent efforts includes: Woodworth (1999) in Liverpool (UK), Marcos et al. (2011, 2013) in Cádiz and Tenerife Island (Spain), Dangendorf et al. (2013) in Cuxhaven (North Sea), Wöppelmann et al. (2014) in Marseille (France), Talke et al. (2014, 2018) in New York and Boston (US) and Ray and Talke (2019) in the Gulf of Maine (USA). Particularly remarkable are the works by Hunter et al. (2003) in Tasmania (Australia), Hannah (2004) in New Zealand, Woodworth et al. (2010) in the Falkland Islands, Testut et al. (2010) in Saint Paul Island (Indian Ocean) and Talke et al. (2020) in the Columbia river estuary (US Pacific coast), since they are based on regions of poor data coverage.

The present work represents an additional effort of sea-level data archaeology and aims at preserving the historical scientific heritage that has been up to now stored in old archives in non-electronic format. The sea-level records presented in the following have been recovered from handwritten logbooks that are archived at the Spanish National Geographical Institute (IGN) in Madrid (Spain).

ALICANTE TIDE GAUGES

2.1 Alicante I (outer harbour)

Our updated, extended sea-level record in Alicante I (outer harbour) results from merging seven different tide gauge records. Figure 1 maps the locations and measurement time period of each tide gauge (see also Table 1). Sea-level observations in Alicante started on July 1st, 1870. Readings initially occurred 4 times per day (at 9:00, 12:00, 15:00 and 18:00 hrs) on a tide pole (tide gauge ID 0101, see Table 1). The benchmark to which all sea-level measurements in Alicante are referred to is called NP1. This benchmark has been used since 1872 as the origin of the Spanish national high-precision levelling network (see https://www.ign.es/web/ign/portal/gds-la-red-mareografos, only in Spanish). The merged sea-level time series is therefore referenced to this benchmark.

The zero of this tide pole from 1870 was located 3.840 m below the benchmark NP1 (Figure 2). These measurements were maintained almost continuously until February 28th, 1874. The only gap lasting a few days occurred around September 27, 1873, during the bombing of the city in the Cantonal Rebellion that took place during the First Spanish Republic (https://en.wikipedia.org/wiki/Cantonal_rebellion). On March 1st, 1874, an Adie floating tide gauge (ID 0201) was installed about 200 m away from the 1870 location (Figure 1), together with a meteorological station. This tide gauge was installed in a stilling well and connected to the sea through a channel. Its zero was 3.454 m below NP1. It operated nearly continuously until March 1924. A long gap occurred between July 1911 and August 1914, a period during which the tide gauge was moved to its second location a further 350 m west (Figure 1). Extant observations are provided in the form of daily averages computed by a mechanical integrator.
The modern location of the tide gauge station on the external side of the dock was built in 1925 (Figure 1) and has been in use since then. The first observations in this site were provided by a Thomson floating tide gauge (ID 0301) located inside a stilling well and were initiated in January 1927. The Thomson gauge registered continuous data on a 60-cm wide paper chart that were converted into hourly observations at the time. This instrument was in operation until 1989, although with numerous interruptions and gaps. For example, data collection stopped from April 1939 until May 1943, and from July 1946 until March 1950. In the late 1960s, the Thomson tide gauge was temporarily replaced by an OTT mechanical recorder (ID 0401) which soon encountered technical problems. The only data provided by the OTT recorder span the period June 1969 to January 1971, with a temporal sampling of 15 min, measured instantaneously. Consequently, the Thomson tide gauge was reinstalled in 1978 and registered hourly values until September 1989. As a result of data gaps, the 1927-1989 record is only ~72% complete.

Digital recording of water levels has been continuous since 1990. Between May 1990 and June 2000, an OTT floating tide gauge (ID 0501) measured hourly data. In January 2000, an additional digital recorder was installed inside the same stilling well (Thales, also made by OTT, ID 0702) to obtain measurements every 10 mins; however, only hourly data are provided in the merged record. For the overlapping period between tide gauges with IDs 0501 and 0702, the latter has been chosen because it is a longer record. Data from the Thales tide gauge are available until December 2013. Starting in January 2014, a Vega radar tide gauge (ID 1603) has been recording sea-level changes with a temporal sampling of 1 min, although, once again, only hourly data are used here. Currently, these observations are transmitted in real time to the data server of the IGN headquarters in Madrid (Spain).
2.2 Alicante II (inner harbour)

In 1953, a new tide gauge station was installed at the inner dock of the harbour (Figure 1). The merged record in this station consists of five tide gauge time series. The first available sea-level observations date from March 1957 measured by a Thomson floating gauge (ID 0303) with hourly temporal sampling. This tide gauge was in service until March 1996 (Table 1). As at Alicante I, digital recorders were installed to register sea-level every 10 mins. Data are provided with the original temporal sampling between 1996 and 1999, and hourly afterwards. The tide gauges included a Thalimedes instrument, manufactured by OTT, (ID 0603) during 1998-1999, a float gauge Owk16 ID 0801 during 1996-2010 and Owk16 ID 0806 during 2011-2013 (Table 1). Since January 2014, sea-level observations were provided by a radar gauge (Vega, ID 1604) with the same characteristics as the radar in the outer harbour. Since 2019, these observations are being transmitted in real time to the IOC Sea Level Station Monitoring Facility (http://www.ioc-sealevelmonitoring.org/, station name Alicante2) and to the Copernicus Marine Environment Monitoring

| Tide gauge type           | Tide gauge identifier | Period of operation (dd/mm/yyyy) | Temporal sampling                          |
|---------------------------|-----------------------|----------------------------------|---------------------------------------------|
| Alicante I (outer harbour)|                       |                                  |                                             |
| Tide pole                 | 0101                  | 01/07/1870-28/02/1874            | 4-daily (9, 12, 15 and 18 hr), but daily averages provided |
| Adie (floating gauge)     | 0201                  | 01/03/1874-31/07/1911 and 01/08/1914-01/03/1924 | Daily averages                             |
| Thomson (floating gauge)  | 0301                  | 01/1927-09/1989                  | Hourly                                     |
| OTT (mechanical recorder) | 0401                  | 06/1969-01/1971                 | 15-min                                     |
| OTT (floating gauge)      | 0501                  | 05/1990-06/2000                 | Hourly                                     |
| Thales OTT (digital recorder) | 0702             | 01/2000-12/2013               | 10-min (but provided hourly)               |
| Vega (radar gauge)        | 1603                  | Since 01/2014                   | 1-min (but provided hourly)                |

| Alicante II (inner harbour)|                       |                                  |                                             |
| Thomson (floating gauge)   | 0303                  | 03/1957-03/1996                 | Hourly                                     |
| Thalimedes OTT (floating gauge, digital recorder) | 0603 | 1998-1999 | 10-min |
| OWK16 (digital recorder)   | 0801                  | 1996-2010                      | 10-min before 2000; provided hourly after |
| OWK16 (digital recorder)   | 0806                  | 2011-2013                      | 10-min (but provided hourly)               |
| Vega (radar gauge)         | 1604                  | Since 01/2014                   | 1-min (but provided hourly)                |

TABLE 1    Tide gauge types, periods of operation and sampling frequency at the Alicante stations. See map in Figure 1 for the location of the identifiers also used in the text
2.3 | Levelling of the tide gauge benchmarks

All tide gauge records in Alicante have been referred to the benchmark NP1, located on the first step of the stairs of the Alicante town hall (Figure 1). Given its relevance to the national levelling network, this benchmark has been extensively monitored, not showing any vertical movements. In particular, its stability was checked by comparing the vertical differences between its position and three benchmarks near the Seismic Observatory located 1.5 km inshore and 30 m high, during 8 levelling surveys that occurred between 1925 and 1974. These benchmarks are called NAP 013, NAP34 and NAP35 (not shown). The differences remained constant over time, thus presenting strong evidence of the stability of NP1. Since 1872, 29 levelling surveys have been carried out in Alicante harbour. These surveys enable estimation of the tide gauge zero with respect to NP1. For benchmarks that were repeatedly levelled, we are able to quantify the rates of vertical motion and hence assess datum stability.

2.3.1 | Alicante I

In the period 1870-1925, during which the sea-level observations are provided by the tide pole and the Adie tide gauge (IDs 0101 and 0201), measurements are directly referred to the NP1. Six levelling surveys took place within this period, directly linking the tide gauge benchmarks and NP1 and establishing the origin of the tide gauge zeros at 3.840 and 3.454 m below NP1, respectively (Figures 2a and S1). No sign of relative subsidence was detected. The formal first-order uncertainties in the levelling are computed as $3\sqrt{D}$ mm where D is the distance between the two consecutive benchmarks in km (Marcos et al., 2011) (note that the formal uncertainties are computed as 1.5$\sqrt{D}$ for modern—after 1930s—levelling surveys). The resulting total errors, computed as the square sum of individual survey errors, for the two periods corresponding to BM 0101 and 0201 are 2.2 and 3.2 mm, respectively, for each of the two periods within 1870-1925. Between 1925 and 2008, the benchmarks used to link the tide gauges in the outer harbour with NP1 are M1 (1925-1960), NAP H270 (1964-1975) and NG M355 (1977-2007) (see Figures 3a and S1). Formal levelling errors in the corresponding elevations due to the distances between levelling benchmarks are 2.9 mm. In addition to these formal uncertainties, subsequent levelling surveys have provided evidence of vertical displacements of the position of these benchmarks. Annual changes in the elevation of these positions with respect to NP1 have been obtained by fitting a linear trend between levelling surveys. For the benchmark M1, the velocities found are 2.4 mm/yr (1925-1934), 1.8 mm/yr (1935-1944) and 0.78 mm/yr (1945-1962), all with uncertainties of around 0.04 mm/yr; these values reflect the time-varying subsidence of the pier where the instrument (and the corresponding benchmark) was placed. An additional benchmark (NAP 016, Figure S1), installed in 1926 very close to the tide gauge position in the outer harbour, has also been levelled in 10 surveys and confirms the subsidence rates in the same section of the pier. The other two benchmarks display, in contrast to M1, an uplift of 0.5 mm/yr (NAP H270: 1964-1975) and 0.2 mm/yr (NG M355: 1977-2007) relative to NP1, probably related to the swell of the concrete ground due to the absorption of humidity.

In the last 10 years, the tide gauge observations in the outer harbour are referred to the NG AB 881 benchmark (Figures 3a and S1). The formal error is again 2.9 mm, since the distance to NP1 is the same. Three levelling surveys linking this benchmark with NP1 have indicated a subsidence of 1.0 mm/yr.

2.3.2 | Alicante II

In the inner harbour, the primary benchmark for the tide gauge is M3 (Figure S1). Formal uncertainty in the elevation with respect to NP1 is 2.9 mm. Changes in the vertical position of M3 with respect to NP1 have been derived indirectly from the levelling of the nearby benchmarks NG J 637 and NAPG 4 (Figure S1); these two benchmarks have been shown to be stable with respect to M3. Vertical displacement in M3 with respect to NP1 has been estimated as subsidence of 0.78 mm/yr during 1955-1971 and 0.4 mm/yr during 1972-2018, which is consistent with the sinking of the pier.

3 | SANTANDER TIDE GAUGES

Sea-level observations from different tide gauges have been available in Santander since 1876 and are ~80% complete through 2018 (Table 2). An Adie floating tide gauge was
initially installed by IGN in July 1876, on the southern side of La Magdalena peninsula (see map in Figure 1 for location). These sea-level observations consist of daily averages obtained from the mechanical integrator (instrument in Figure 3). The first part of the time series at the initial location lasted until 1914; observations were referenced to a local benchmark. In 1920, the same instrument was moved west and reinstalled in the location of the present-day tide gauges in Santander harbour, at the Puerto Chico dock (Figure 1), and its observations were referred to a different local benchmark. The Adie tide gauge was in operation until 1924. In 1920, a secondary Mier syphon-type tide gauge was also installed in the same stilling well and referred to the same benchmark. A syphon-type tide gauge uses a narrow water pipe submerged into the ocean through the stilling well and connected to a mercury manometer that, in turn, is able to vertically displace a small float. Figure 3 shows a picture of the Adie and the Mier tide gauges used in Santander. Measurements are also available as daily averages and lasted until July 1925. From January 1925 to December 1928, additional observations occurred using an Iglesias syphon-type tide gauge, provided, once again, as daily averages.

In 1943, the Spanish Institute of Oceanography (IEO) installed a new float tide gauge in the same location and stilling well as the 1920 IGN gauge (Figure 1). A continuous hourly record is available since then. Monthly averages are compiled and distributed by the PSMSL (station ID 485 (Santander I) psmsl.org/data/obtaining/stations/485.php). Puertos del Estado (PdE) (Spanish Harbours Authority) installed a SRD acoustic tide gauge in 1992, replaced by MIROS radar gauge in 2008. The acoustic and radar sensors were operating simultaneously during 1 year, following GLOSS recommendations, in order to determine the impact of the technology upgrade on the long-term time series. The merged final time series from PdE (1992 to present) was constructed according to this by Pérez-Gómez et al (2014) and monthly data
The raw temporal sampling has now increased to 1 min resolution in both modern IEO and PdE tide gauges. Both are related to the same local benchmark NGU-84 (Figure S2). The modern long records are currently integrated and regularly updated within national (IEO, PdE) and international data bases such as the Permanent Service for Mean Sea Level, CMEMS In-Situ TAC and others (e.g. Woodworth et al., 2017) from which quality-controlled data can be downloaded.

### 3.1 Levelling of the tide gauge benchmarks

The historical and modern tide gauge records in Santander can be merged together in a consistent and continuous sea-level record using extant surveys that can be related to the NGU-84 benchmark (Figure S2). The NGU-84 benchmark, inside the present-day tide gauges building, is also the reference benchmark for IEO and PdE tide gauges, is considered stable, and is part of the national levelling network.

Sea-level observations provided by the three historical (prior to 1928) tide gauges in the two locations in Santander were referred to local benchmarks, situated nearby the instruments (Figure S2). The relative elevation between these two local benchmarks is indicated in Figure 2b. The 1876-1914 series was referred to a benchmark that was 2.066 m ± 7.6 mm above the present-day NGU-84 benchmark. The 1920-1928 series was referred to a benchmark that is 0.949 m ± 2.3 mm above NGU-84. The modern (1943-present) tide gauge record is directly referred to the NGU-84 benchmark.

### 4 MERGED SEA-LEVEL RECORDS

Figure 4 represents the two merged sea-level records in Alicante at the outer and inner locations of the harbour, plotted with indications of their temporal sampling as listed in Table 1. The vertical reference has been set to be 10 m below the benchmark NP1, following the rule established by the PSMSL to avoid negative numbers in sea-level records (Holgate et al., 2013).

Despite the careful analysis of the levelling surveys and references to the several tide gauge benchmarks in Alicante harbour, datum shifts cannot be ruled out, especially given the length of the record. Meta-data found in logbooks is often incomplete and does not justify further corrections in the time series. A usual practice is to compare the sea-level record with a neighbouring time series that is expected to show similar behaviour, the so-called ‘buddy-checking’ (Pugh and Woodworth, 2014). In the case of Alicante, the

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**FIGURE 4** Sea-level time series at Alicante I, Alicante II and Santander, with their original temporal sampling (Table 1). Shadowed colours indicate changes in the sampling. Note that vertical scale for Santander (lower panel) is different to those for Alicante.
only record in the vicinity spanning a comparable time period is Marseille (Wöppelmann et al., 2014), located on the French Mediterranean coast, about 700 km north of Alicante. Despite the distance, both tide gauges are in the same Western Mediterranean basin and are therefore expected to be representative of the same long-term sea-level changes. In Figure 5, monthly deseasonalized time series of Alicante and Marseille are plotted together. The monthly sea-level record from Marseille has been obtained from the PSMSL data base (www.psmsl.org). To allow for a better comparison, both records display the same averaged value in the most recent 20-year period. For their common period starting in 1885, the linear trends in Alicante and Marseille are 0.65 ± 0.04 and 1.28 ± 0.04 mm/yr, respectively. Differences in relative sea-level trends could be explained by differential vertical land movements (VLM) between the two sites. However, trends of VLM derived from short-term nearby Global Navigation Satellite Systems (GNSS) observations suggest both sites are stable, with negligible vertical motion of 0.34 ± 0.20 mm/yr in Alicante and 0.18 ± 0.19 mm/yr in Marseille (Santamaría-Gómez et al., 2017). Likewise, differences in the modelled Glacial Isostatic Adjustment component of vertical land movement are of the order of 0.08 mm/yr (ICE5G model, Peltier, 2004), thus too small to account for the bias alone. Since the linear trend value in Marseille is consistent with that in the neighbouring record in Genova (Marcos and Tsimplis, 2008), such a difference suggests a datum shift in Alicante. A careful visual comparison shows a vertical difference of the order of 10 cm between years 1911 and 1914 (vertical line in Figure 5, upper panel), when the tide gauge was changed from its initial location. The linear trend increases to 0.91 ± 0.05 mm/yr, when the period before 1911 is discarded, approaching the value in Marseille that keeps the same trend. Also, there is a data gap around 1907. Nonetheless, the inter-annual variability in Alicante from 1870-1910 closely follows the Marseille time series, confirming that the gauge series is useful for investigating shorter term variability during this time period.

The historical sea-level record in Santander is shown in Figure 4 (lower panel). The recovered time series has been merged with the modern IEO record starting in 1943, since both are referred to the same benchmark. The merged record has been converted into monthly values and the ‘buddy-checking’ exercise has been performed using the sea-level record from Brest, the longest one in the region, located 500 km northwards and available since 1807 (Wöppelmann et al., 2006; Wöppelmann et al., 2008). As in the case of Alicante, the two time series have been reduced to a common mean for the last 20 years of data for a better comparison. The monthly deseasonalized time series are plotted in Figure 5 (lower panel). The comparison clearly highlights anomalous datum shifts in Santander during the periods 1883-1886, 1890-1898 and 1900-1908 (shadowed areas in Figure 5, lower panel). The earlier period, however, displays a strong consistency between the two records, in terms of vertical referencing and variability. In consequence, the linear trends from 1876-2018 are virtually identical with 1.49 ± 0.05 and 1.43 ± 0.04 mm/yr in Santander and Brest, respectively. Both stations have no measurable VLM, GNSS rates being 0.01 ± 0.11 mm/yr in Brest and 0.03 ± 0.17 mm/yr in Santander. Thus, the Santander time series bolsters our confidence in historical sea-level rise patterns in the Bay of Biscay. The monthly deseasonalized series in Santander also closely follows inter-annual variability at Brest within time periods of a consistent datum.

5 | FINAL REMARKS

The Spanish National Geographical Institute (IGN) carried out the first regular sea-level observations in Spain. The historical

![Figure 5](image-url)
data set contains records dating back to the 19th century at a few stations that have been archived for decades in logbooks. This work includes the last two sea-level records known to be remaining after the publication of the time series of Cádiz (Marcos et al., 2011) and Tenerife Island (Marcos et al., 2013). The new longer time series for Alicante and Santander will be added to international sea-level databanks, contributing to extending the existing limited long-term sea-level information. These new sea-level records are regularly updated by the current operators (IEO and PdE in Santander, IGN in Alicante) and can be obtained from their data servers as well as from international data bases. Since the historical time series are provided referenced to the modern benchmarks, the addition of the most recent data is straightforward, provided adequate maintenance of existing stations continues.

The three sea-level time series, Alicante I, Alicante II and Santander, are the result of merging various tide gauge records. In each case, we have carefully investigated every high-precision levelling survey carried out in the vicinity of the tide gauges, whether they were aimed at controlling the tide gauge benchmarks or not. Despite making use of all available levelling information, some doubts remain about the datum continuity of the time series. Anomalous periods and linear trends become evident when comparing with nearby sea-level records. Unfortunately, no other information was found in the archives of the IGN that allows us to correct apparently erroneous periods. Therefore, we recommend using the long-term (multi-decadal to centennial) variations with caution at Alicante I and Santander, and only after a detailed reading of this manuscript. We believe, nevertheless, that the three sea-level time series are valuable for studies dealing with shorter term sea-level changes, from decadal to inter-annual and seasonal, and, given the high-frequency temporal sampling, also for extreme sea levels.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available ath-https://doi.org/10.5285/9f6e88-495-bc84-775e-e053-6c86a bc0e04b and https://doi.org/10.5285/a7304 d52-9860-4aed-e053-6c86a bc0ab5a Learn more about the Open Practices badges from the Center for OpenScience: https://osf.io/tyyxx/wiki.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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