https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

Open Access Earth System Science Data Discussions

Extension of high temporal resolution sea level time series at Socoa (Saint Jean-de-Luz, France) back to 1875

Md Jamal Uddin Khan[1], Inge Van Den Beld[2], Guy Wöppelmann[1], Laurent Testut[1], Alexa Latapy[2], Nicolas Pouvreau[2]

[1]LIttoral ENvironnement et Sociétés - UMR 7266, ULR/CNRS, La Rochelle, 17000, France
[2]Service Hydrographique et Océanographique de la Marine (SHOM), Brest, 29200, France

Correspondence to: Md Jamal Uddin Khan, jamal.khan@univ-lr.fr

Abstract. In this data paper sea level time series at Socoa (Saint Jean-de-Luz, Southwestern France) is extended in a data archaeology exercise. We have catalogued water level records stored in ledgers and charts, as well as other associated documents (metadata) in thorough research of national and local archives. An extensive effort was made to rescue these documents by archiving them in digital formats. Based on this large set of rescued documents, the Socoa time series is further extended back in time by about 40 years, at hourly (for ledgers) to 5-minutes (for charts) sampling. Analysis of the precise levelling information reveals that the datum of the tide gauge site has been stable. We assessed the consistency of this new century-long time series based on nearby tide gauge data. Although the overall timeseries is generally consistent, siltation is found to be a recurrent problem of the stilling well which impacted some part of the extended data. However, being a high temporal resolution sea level time series spanning more than 100 years, this new dataset will be useful for advancing climate research, particularly the decadal scale variations in the North Atlantic, as well as the storminess and extreme events along the French Basque coastal region.

1 Introduction

Sea level records are one of the oldest instrumental records that have a crucial contribution to our understanding of contemporary sea level variability and climate change (Ekman 1999, Church et al. 2013). Based on the available study on the long-term sea level data, the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on the Ocean and Cryosphere in Changing Climate (SROCC) reported it to be *very likely* (66-100% probability) that the Global Mean Sea Level (GMSL) has been rising at a rate of 1.5±0.4 mm/year between 1901 and 2010 (Oppenheimer et al. 2019). The assessment of the sea level rise occurred during 19th century relies heavily on sparsely located long-term in situ tide gauge datasets (e.g. Dangendorf et al. 2017). A subset of these long time series became accessible for scientific community through discovery, digitization, and reconstruction of a new or extended sea level timeseries from archival records – which is known as sea level data archaeology (Woodworth, 1999).

Over last few decades, Data archaeology has been applied over the globe to construct and study long sea level variability and change (e.g., Woodworth 1999, Hunter 2003, Talke et al. 2018). For instance, Woodworth (1999) recovered and analysed the

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

mean high-water level recorded at Liverpool starting from 1768. Similarly, Woppelmann et al. (2006a) applied data archaeology to reconstruct a sea level series at Brest back to the beginning of the 18th century. Both studies concluded a similar result – a rising trend from the beginning of the 20th century with an acceleration towards the second half (Woppelmann et al. 2008). In the southern hemisphere, where the data coverage is generally sparse, Testut et al. (2010) recovered water level measurements recorded in 1874 on Saint Paul Island in the southern Indian ocean. Combining with recent measurements they revealed a statistically zero relative sea level trend. Similarly, Hunter (2003) recovered and analysed intermittent sea level records made in Port Aurthur, Tasmania (southern Australia) reporting a sea level trend of 0.8±0.2 mm/year. At local scale, some data archaeology studies combine multiple nearby historical tide gauge records into one long timeseries for sea level trend analysis (Marcos et al. 2011; 2021; Woodworth, 1999). Whereas, regionally, Hogarth et al. (2020) combined data archaeology, numerical modelling, and statistical minimization approaches to further extend the mean sea level record over the British Isles. They estimated a robust regional mean sea level trend of 2.39±0.27 mm/year with an acceleration of 0.058±0.030 mm/year^2 since the mid-twentieth century. Thanks to the long timeseries, new long-term signals pertinent to the interpretation of observed GMSL rise and acceleration are being discovered. One such example is the study by Ding et al. (2021). They report a 64-year oscillation in GMSL and raises concern about the characterization of the contemporary GMSL acceleration estimates.

GMSL rise also raises questions regarding associated long-term changes in tide, which requires high frequency sea level observations. During the first half of the 19th century, automatic mechanical tide gauges started appearing paving the path for systematic continuous measurements of water levels at high frequency (Woppelmann et al 2006b). Taking advantage of the archaeology of such high-frequency long-term sea level records, Pouvreau et al. (2008) analyzed the secular trend in M2 evolution at Brest. Another contemporary example of such analysis is Colosi and Munk (2006), who looked at the Honolulu tide gauges and attempted to explain the secular trend in tidal constituents. Aside from the secular trend, Pan and Lv (2021) found a quasi 60-year oscillation in the global tide.

High-resolution past tide gauge timeseries also proved very useful for the analysis of extreme sea level (ESL), which is a major societal concern due to ongoing sea level rise (Oppenheimer et al. 2019). Based on the recovered hourly timeseries at the Marseille tide gauge by Woppelmann et al. (2014), Letetrel et al. (2010) analysed the temporal variability of ESL and found a secular variation of extremes relating to the long-term evolution of the mean sea level. Talke et al. analyzed the ESL evolution at New York (Talke et al. 2014), and Boston (Talke et al. 2018). They illustrate how long-term sea level can help to separate the relative contribution of climate, and local changes. By aggregation and further quality control of single datasets like in Marseille, and New York, Global dataset like GESLA has been developed over time (Woodworth 2016). Such a global dataset allowed global and regional analysis of tide (Piccioni et al. 2019), surge (Tadesse et al. 2020), extremes (Marcos et al. 2015), as well as the non-linearity of tide-surge (Arns 2020). Although sea level rise is projected to increase the probability of ESL worldwide (Muis et al. 2016), the amplification varies regionally depending on the local processes (Rasmussen et al. 2018). SROCC concluded with *high confidence* (meaning high agreement and robust evidence in the available literature) that consideration of localized storm surge processes is essential to monitor the trend in ESL. Such monitoring requires reliable

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

high-resolution observations. Yet, most of the stations in GESLA have a timeseries less than 50-year long (Woodworth 2016). Data archaeology can be a solution to this lack of data, as previous studies indicates that there are potentially large number of instrumental records that can be rescued over the world (Bradshaw et al. 2015).

In the context of the lack of long-term high temporal resolution records for the assessment of short to long-timescale processes, this article is a data rescue and archaeology effort to make available high temporal resolution long-term sea level timeseries at Socoa. Socoa is located in Saint-Jean-de-Luz, France, along the Basque coast in the Bay of Biscay, which is a 200 km coast facing the Atlantic covering the north of Spain and South-West of France (Figure 1). The surrounding region is dominated by a strong tide (meso-tidal) and energetic waves (Dodet et al. 2019). The tide gauge station at Socoa was established in 1875. However, the earliest available data in the French reference repository (e.g., https://data.shom.fr/donnees/refmar/95, last accessed 10 Apr. 2022) starts from 1942, with continuous recording from 1964 only (Arnoux et al. 2021).

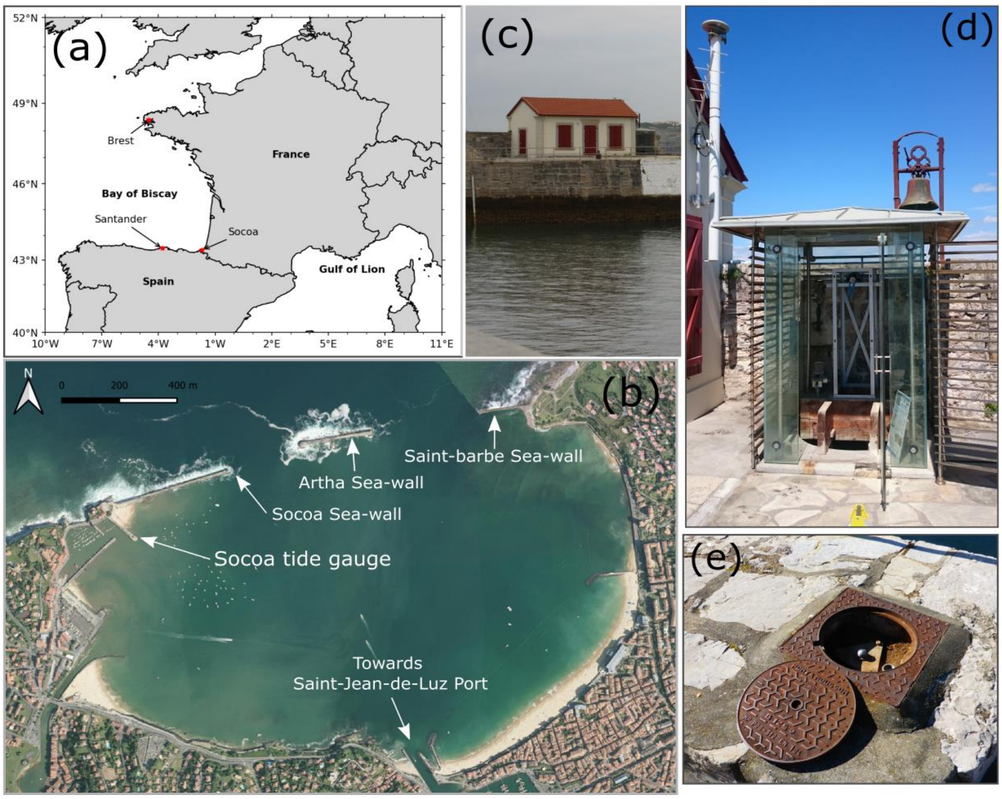

Figure 1: (a) Study area indicating the location of the Socoa tide gauge and other tide gauges used in this study (b) The satellite view of the study area (IGN geoservices, https://geoservices.ign.fr/). (c) A view of the tide gauge surroundings and the housing location. (d) The tide gauge house over the top of the stilling well. (e) The nearby tide gauge benchmark IGN O.A.K3L3-5-IV.

In Section 2 of this paper, the history of the Socoa tide gauge is presented and the various instrumentation periods and list of the rescued documents (containing data and metadata) are discussed. The rescue process and analysis of the time series are described in Section 3, which is followed by an assessment of the quality control and data quality issues in Section 4. In Section

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

5, we present a trend analysis. Finally, this paper ends with a concluding remark in Section 6. The computational notebook (Python/Jupyter) and raw data are also provided with the final (cleanest) dataset.

2 History of Socoa tide gauge station and rescued documents

The Socoa tide gauge station, which included water level and meteorological instruments, was established during the 1873-1875 period. A dedicated housing with an adjacent stilling-well system was built to host the original tide gauge, for handling the daily tasks of the gauge keeper, as well as to store the paper charts (Figure 1c). Several water level instruments were operated during various periods covering the 19th and 20th centuries and followed on into the 21st century with modern technology that is still currently operating (Fig. 1 in Martin Miguez et al. 2008). The description of each instrumentation period is provided in the following sub-sections along with the rescued data and metadata of the sea level observations in this study.

2.1 The Chazallon tide gauge period: 1875-1920

During the 1840s, several float-type tide gauges devised by Antoine M. R. Chazallon (1802-1872) were installed along the French coasts. A schematic of the tide gauge is shown in Figure 2c. Typical to float tide gauges, the displacements of the float by the change in water level is reduced through mechanical means (reducer) and recorded in a time-controlled rolling paper (called chart) (IOC 1985). One of the tide gauges was installed in La Rochelle (Vieux Port) and operated from 1863 to 1874 (Gouriou et al. 2013). This tide gauge was transferred to Socoa station in 1875. At Socoa, the float of the tide gauge was installed into a stilling well, located just nearby the housing where the device was installed.

Two types of historical water level records are found for the Chazallon tide gauge period – 1) a subset of charts, 2) transcription into ledgers. The ledgers are 32x49cm paper documents containing transcription of water levels done by an observer from the original charts. The ledgers (Supplementary Figure S1) and charts are stored at the Shom archive located in Brest.

Chazallon tide gauge was operational until 1920 when most tide gauges around the French coast were discontinued. Until then, the tide gauge was operated by the Service Hyrdrographique de la Marine (SHM), the predecessor of the current Service hydrographique et océanographique de la Marine (Shom, https://www.shom.fr/).

2.2 The Brillie tide gauge period: 1950 to 2004

During 1950, a Brillie type float tide gauge (large model type, Robertou 1955) was installed (Figure 2d) in the former stilling well. Each chart for large type model is of 72x50 cm in dimension. The x-axis of the paper is divided into 24 divisions (corresponding to each hour), and each hourly division is further subdivided into 10-minute subdivisions. On the other hand, with a 1/10 reduction, the y-axis represents 5m (50cm x 10) height and are divided into 25cm with a subdivision of 5cm. No documentation was recovered during the archival search regarding the installation and operation of this tide gauge, except the physical existence of the tide gauge itself till 2004.

The recording of water levels starts in December 1950 by the Service Maritime des Ponts et Chaussées. In total 2477 charts spanning the period December 1950 to 2001 were recovered from the local archive - Archives des Pyrénées-Atlantiques (henceforth AD64, http://archives.le64.fr/). No data were found for 2002-2003.

The recording of water level curves in the charts during the Brillie tide gauge period was done in the legal time of France (See 3.2 for further details). Each curve in the charts represents one day of water level record, and each chart is found to contain multiple days of recording (Supp. Figure S1c). Typically, up to 14 days of sea levels were recorded in these paper charts. In most cases, the charts were accompanied by a check sheet (Feuille de contrôle) of A4 size, which are obviously an important part of the data rescue. See Figure 2b for the availability of the check sheets.

It is interesting to note here that in the currently available archives (e.g., Shom, PSMSL), there are data available during the World War II (WWII) period – from November 1942 to May 1944. While 44 charts were found in the Shom archive at Brest, covering this period, the, rescued metadata do not report there was a tide gauge operating at Socoa. After inspection, we found a different paper size of these charts compared to Brillie or Chazallon, which indicates that it was a different tide gauge. In addition, the paper charts bear German markings. Local historians confirm that it was indeed another tide gauge, installed by Germans, on the other side of the Socoa bay. The data during WWII appears to be consistent with the rest of the record based on tidal analysis. No record was found in between this German tide gauge (1944) and the Brillie tide gauge (1950).

2.3 The modern instrumentation: 2004 to ongoing

With the advent of the modern RONIM sea level measurement network (Martin Miguez et al., 2008), the Brillie tide gauge at Socoa was decommissioned and replaced with a digital radar gauge in 2004 (Figure 2e). This radar gauge is currently co-located with a continuously operating geodetic Global Navigation Satellite System (GNSS) station (https://www.sonel.org/spip.php?page=gps&idStation=835). The antenna of the GNSS station is visible in Figure 1c. This tide gauge is maintained by Shom. Its sea level data and metadata are available at the Shom data portal (see https://data.shom.fr for high-frequency and post-processed quality-controlled data). The tide gauge is equipped with, and accessible through the Global Telecommunication Systems (GTS) network, which enables a real-time data flux. This data flux enables real-time monitoring of the gauge, for instance via the Intergovernmental Oceanographic Commission (IOC) sea level monitoring facility (see http://www.ioc-sealevelmonitoring.org/station.php?code=scoa2). Note that the data from the IOC facility should not be used for any high-precision application, as its main design and procedures have been monitoring the operational status of the gauges (Aarup et al. 2019).

It is noteworthy here that at Socoa, the position of the tide gauge remains the same over its full period of observation from November 1875 until now through various instrumentation periods. The modern tide gauge is operating within the same stilling well, hence preserving the spatial and environmental continuity with the past measurements. There is some caveat of modifications done on the stilling well infrastructure in the early recording period, which we will illustrate later.

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

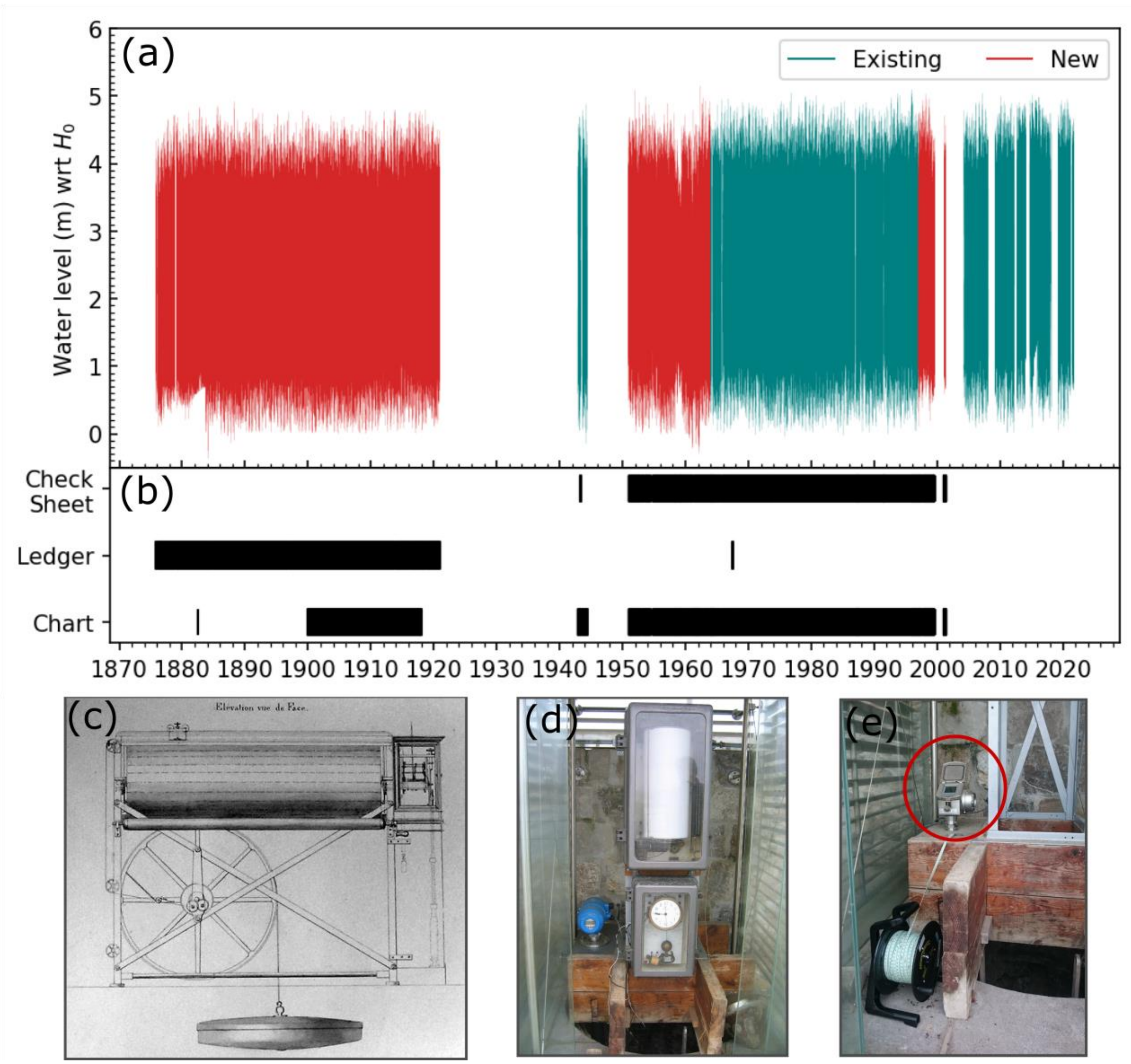

Figure 2: (a) Timeseries of water level at Socoa with digitized data (in red the new datasets from this study). (b) Coverage of the rescued Registries (MR), Charts (MM), and associated check sheets (FC). (c) A schematic of the Chazallon tide gauge (adopted from Pouvreau et al. 2008). (d) A photo of the Brillie type tide gauge operated till 2001 and (e) the modern radar gauge (Photo taken by authors during a field campaign in 2017).

A chronology of the available water level records, instruments, medium of recordings, time system, sampling and archive is summarised in Table 1. Not being part of the data archaeology exercise, the processing of the modern instrument record starting in 2004 is not further discussed in the following sections.

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

Open Access Earth System Science Data Discussions

Table 1: Overview of sea level data and their coverage at Socoa

Period	Instrument	Medium	Sampling and Time system	Archive
1875-11-01 10:50:20 to 1893-12-31 23:10:37	Float (Chazallon)	Ledger	15 min, AST	Shom
1894-01-01 00:06:43 to 1897-12-31 23:06:43	Float (Chazallon)	Ledger	15 min, MST	Shom
1898-01-01 00:06:43 to 1920-12-14 12:06:43	Float (Chazallon)	Ledger	1 hour, MST	Shom
1942-11-20 23:00:00 to 1944-05-29 22:00:00	Float (Unknown)	Chart	1 hour, UTC+1/+2	Shom
1950-12-18 11:30:00 to 1963-12-23 11:25:00	Float (Brillie)	Chart	5 min, UTC+1	AD64
1964-01-03 23:00:00 to 1997-01-07 08:00:00	Float (Brillie)	Chart, Digital	1 hour, UTC+1 till 1976, UTC+1/+2 since 1976	AD64, Shom
1997-01-07 10:00:00 to 1999-08-27 08:45:00	Float (Brillie)	Chart	5 min, UTC+1/+2	AD64
2001-02-20 08:15:00 to 2001-05-29 08:20:00	Float (Brillie)	Chart	5min, UTC+1/+2	AD64
2004-04-13 14:00:00 to 2004-05-31 23:00:00	Float (Brillie)	Chart, Digital	1 hour, UTC+1/+2	?
Only hourly till 26/04/2011	Radar (Krone Optiwave 7300C)	Digital	1 hour, UTC	Shom
Highres and hourly from 26/04/2011 to date	Radar (Krone Optiwave 7300C)	Digital	1 hour, UTC	Shom

* Inferred from the chart types.

AST: Apparent Solar Time.

MST: Mean Solar Time.

UTC: Universal Time Coordinated.

SHOM: Service hydrographique et océanographique de la Marine

AD64: Archive Departmental 64 - Pyrénées-Atlantiques - Béarn Pays basque

155 **2.4 Supplemental metadata**

During the archive research, other administrative documents, where the Socoa tide gauge was mentioned, were consulted. These documents include tide gauge journals for the Chazallon tide gauge period, the correspondence with the ministry, the

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

engineering and hydrographic survey reports, the quotes for works, drawings etc. The corresponding parts of the documents mentioning the Socoa tide gauge were also transcribed, which form an ancillary part of the available metadata. The hydrographic survey reports were of particular interest to assess the datum continuity of the tide gauge records.

The transcript of the relevant part of the tide gauge journals are provided with the data as yearly document. The excerpts of metadata documents from the archives of Service historique de la Défense (SHD) at Brest (SHD-Brest), Rochefort (SHD-Rochefort), Vincennes (SHD-Vincennes), AD64, and SHOM archive are also provided as supplementary files to the dataset.

3 Digitization and reconstruction of the time series

3.1 Scanning and digitization

3.1.1 Ledgers

The water level recorded by the Chazallon tide gauge during the 1875-1920 period is stored through two mediums – charts and hand-written ledgers. The charts are found to be very old, large, and structurally precarious for scanning and digitization. The rescue of these delicate documents could not be pursued under current equipment constraints. Hence, only the ledgers were found to be suitable for scanning and rescuing with the available equipment at hand. The scanned documents are stored as PDF (portable document format) files, weighing 1-1.2 MB each.

Once the scanning was complete, the process of converting the hand-written text to data (digitization) was done manually from the scanned document to a computer spreadsheet. The paper for the ledgers was designed for transcribing water levels at 15-minute intervals. However, the water levels were transcribed at 15-minute intervals till 1897 only. Afterwards, the transcriptions were done at a 1-hour interval. To speed up the manual digitization process, a choice was made to digitize the water level record at hourly intervals.

For the Chazallon tide gauge period starting from November 1875 to December 1920, 541 ledgers were recovered amounting to 45 years of sea level records. More than 390k values of sea level were digitized from the ledgers, which corresponds to several weeks of full-time work. During digitization, the time data were digitized as-is on the ledgers. Sea level from 1875 to 1893 were recorded in Apparent Solar Time, and from 1894 to 1920 it was recorded in Mean solar time. The conversion of these time records into UTC is described in Section 3.2.

3.1.2 Charts

Unlike the early Chazallon-era charts, the whole recovered archive of the charts produced by the Brillie type tide gauge covering the period starting from 1942 to the early 21st century is scanned (with a scanner) from their original paper form, thus can be considered rescued. The check sheets, which were attached to most of the charts were also converted into digital form by cameras and later used as metadata for identifying problems, especially related to the slowing down of the clocks (See Section 4.2), as well as for applying corrections, where appropriate.

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

To extract the water level from the chart images, a specialized open-access software called Numerisation des Niveaux d'EAU (NUNIEAU) was used (Ullmann et al. 2011). For a given chart image, this software can trace the recorded water curve-line based on a colour-separation technique. Additionally, the software has built-in features to assign time and height scales in the chart (Supplementary Figure S3). Since the algorithm is based on colour separation, the water levels are easier to extract from a cleaner chart. However, the rescued charts used in this work have been in archives for quite a long time and like all other paper-based documents are prone to wear and tear during handling, and degradation due to fungal attacks. During the scanning phase of the charts, the charts were visually sorted into several categories (Supplementary Figure S2). The charts in the first category are in "good" condition, which does not need any further image processing to be applied before passing it through NUNIEAU software. In the second category are the charts which are damaged from mould. They were sorted into two sub-categories - mildly damaged, and strongly damaged. Typically, the mildly damaged charts are found to be still processable through the processing chain without much problem. In the worst-case scenario of strongly damaged charts, water level records are fully covered by mould which translated essentially in the loss of data during those periods. Finally, in the third category are the charts where the recorded water level curve lines were found faint - either fully or partially. These fainted lines happened mostly due to ink shortage, and often the observer in charge traced manually the lines using a pencil/pen afterwards. Further image processing was applied on these faint charts of the third category to enhance the contrast as much as possible so that they could be processed using NUNIEAU (Supplementary Figure S4).

Prior to this study, an hourly record of sea level at Socoa from 1964-1996 existed in digital form and is available from the Shom data portal (https://data.shom.fr). Hence, we applied the water level extraction method using NUNIEAU software only on the charts that are outside the range of pre-existing digitized data. From 1950 to 2001, the number of newly digitized charts amounts to 777. Among them, 18.3% (142 charts) were found to be in "good" condition (Figure S2). 50 charts were found to have mild mould (mildly damaged), and 32 of them were found with highly covered by mould (strongly damaged). By far most of the documents, as many as 553 charts (71.2% of the digitized charts), were found to be of the third category with fainted water level curve lines. Consequently, despite being software-based, the overall process was time-consuming, like manual digitization from ledgers, as well as challenging. In addition, multiple days of water level were recorded in a single chart, partially overlapping themselves. The problem was overcome applying dedicated masks to separate each day of record. The zero of the water level curves was also set manually for each chart within the NUNIEAU parameterization. Afterwards, NUNIEAU was applied to extract the water level at a chosen 5-minute interval. This time interval corresponds to 20 pixels in the x-axis of the scanned charts (scanned at a resolution of 200 dpi). Going below this interval is useless as the higher frequency fluctuations are mechanically passed filtered by the stilling well (IOC 1985).

3.2 Time systems and conversion

Once the scanning and digitization were performed, the next important step was to reduce the records into a consistent time system, in this case, the Coordinated Universal Time (UTC) in zero-hour time zone UTC±00:00 (henceforth denoted as

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

UTCZ). Over the recording period of the Socoa tide gauge, several time systems were used as described in Section 2 and listed in Table 1.

3.2.1 Apparent and Mean Solar Time

As noted by Wöppelmann et al. (2014), Apparent Solar Time (AST) was used in the earlier days of the Chazallon tide gauge era despite the Mean Solar Time (MST) being the legal time since the early 18th century. Likewise, at Socoa, the metadata confirm that, from 1875 to 1893, the transcribed records into the ledgers are in AST. It was ultimately changed in 1894, and until 1920 the transcribed records are in MST.

AST is determined from the position of the sun, its highest point of the day above horizon being noon, typically read from a sundial. On the other hand, MST corresponds to a fictitious Sun, whose apparent movement is circular at a uniform speed over the sky year-long. Of course, this is not true: the orbit is elliptical and the speed changes along the orbit from a minimum at aphelion to a maximum at perihelion (Kepler 1st and 2nd laws of planetary motion). The position of apsides translates into an overall slower sundial timing from January to June and a faster one from July to December. This general b ehaviour is further modulated by the inclination of the Earth's axis of rotation. The inclination causes a slower sundial during 21st December (winter solstice) to 21st March (vernal equinox), and 21st June (summer solstice) to 21st September (autumnal equinoxes). The difference between AST and MST throughout the year is known as the 'equation of time' (Müller 1995).

We adopted the equation of time from the almanac published by Bureau Des Longitudes (2011). The equation of time, E, is expressed as:

$$\begin{aligned} E \quad &= 7.362 \times sin(M) - 0.144 \times cos(M) + 8.955 \times sin(2 \times M) + 4.302 \times cos(2 \times M) \\ &+0.288 \times sin(3 \times M) + 0.133 \times cos(3 \times M) + 0.131 \times sin(4 \times M) + 0.167 \times cos(4 \times M) \\ &+0.009 \times sin(5 \times M) + 0.011 \times cos(5 \times M) + 0.001 \times sin(6 \times M) + 0.006 \times cos(6 \times M) \\ &-0.00258 \times t \times sin(2 \times M) + 0.00533 \times t \times cos(2 \times M) \end{aligned}$$

Here, t is the time difference to 2000-01-01 00:00:00 (in year, negative for earlier years). M is the mean anomaly, the angle from the periapsis of the elliptical orbit to the mean Sun, which value varies from 0 to 2π. As Earth revolves 360 degrees (2π) in circa 365.25 days, the average angular velocity of the Earth around the mean Sun is $\frac{2\pi}{365.25}$ radians per day. We can take the perihelion as the starting point of the revolution around the sun. The periapsis presently occurs around 2-4 days (an average value of 2.507 days used in our computation) after 1st January, leading to a phase lag of $\frac{2\pi \times 2.507}{365.25}$ radians. Hence, M is $\frac{2\pi}{365.25} \times (day - 2.507)$. In our computational notebook, this computation is implemented as $M = 6.240060 + 6.283019552 \times t$ (in radians). Once the equation of time, E, is computed, adding its results to the AST times gives them in MST. Although the equation is fitted for 1900-2100, using the same equation before late 1800 induces only minor errors, hence it was used in this study as is given by the Bureau Des Longitudes (2011).

To convert from MST to UTC, a correction of 4 minutes per degree of longitude difference between Socoa and Greenwich (zero-longitude) was applied. This amounts to 404 seconds to be added to the MST recorded in Socoa to get the time in UTCZ.

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

3.2.2 Legal time

During the Brillie tide gauge period, the measurements were recorded in the legal time. The history of the legal time in France is long, and we present here a summary to the detail account of Poulle (1999). Since 1891 the legal time of Metropolitan France was established as the MST in Paris. In a law enacted in 1911, a correction of 9 minutes 21 seconds was applied to Paris MST to define the new legal time as the Greenwich Mean Time (GMT). In 1923, the law related to legal time was amended to introduce 'summertime' (Typically last Sunday of March to last Sunday of October), when the clocks are advanced by 1 hour. During 1940-1941, timekeeping was different between German-occupied and -free areas. However, during 1942-1944, the legal time throughout France was essentially GMT+2 during summer and GMT+1 during winter. Post WW2, France switched to using only GMT+1 on 18 November 1945. The Universal Coordinated Time (UTC), formulated in 1960, gradually replaced GMT. GMT is essentially equivalent to Zero UTC (UTCZ) within 1 sec. Hence, in the context of this paper we used GMT+1 and UTC+1 interchangeably. Until 1975, the legal time corresponds to UTC+1. In 1976, daylight saving time was adopted again in Metropolitan France with UTC+2 during summertime (Last Sunday of March to last Sunday of October) and UTC+1 otherwise, which continues to this date.

In theory, to convert a time record from one time zone to another time zone in GMT or UTC is trivial, simply by accounting for the hour difference of the time zone in question. However, the conversion gets complicated due to clock shifts during summer and wintertime. For example, it was found that the charts kept recording at the time system (summer or wintertime) of the paper chart installation. The clock was adjusted to the new shifted time when the chart paper was changed. Thus, the metadata associated with these changes were used to properly apply the time difference between legal time and UTCZ.

3.3 Vertical datum and continuity

Since the installation of the tide gauge at Socoa in 1875, the water level has been recorded relative to the 'zéro hydrographique' (ZH), that is the French nautical chart datum. ZH has been in use since the nineteenth century by the French hydrographers (Woppelmann et al. 2014). A local set of tide gauge benchmarks are usually grounded around the tide gauge and interconnected with levelling to represent the ZH. Additionally, the practice in France is to include a tide pole and set its zero-measurement mark to the ZH (Woppelmann et al. 2006b), but it was not adopted for Socoa tide poles. Thanks to the rescued documents on the levelling measurements during past hydrographic surveys, it was possible to reconstruct the relationship of the tide gauge and tide pole zeros to the current benchmarks, and subsequently to assess the continuity of the ZH at Socoa (Figure 3). The current primary benchmark of the Socoa tide gauge is identified as O.a.K3L3-4-II, which is also part of the national levelling network under the mapping agency (IGN) responsibility (Shom 2020).

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

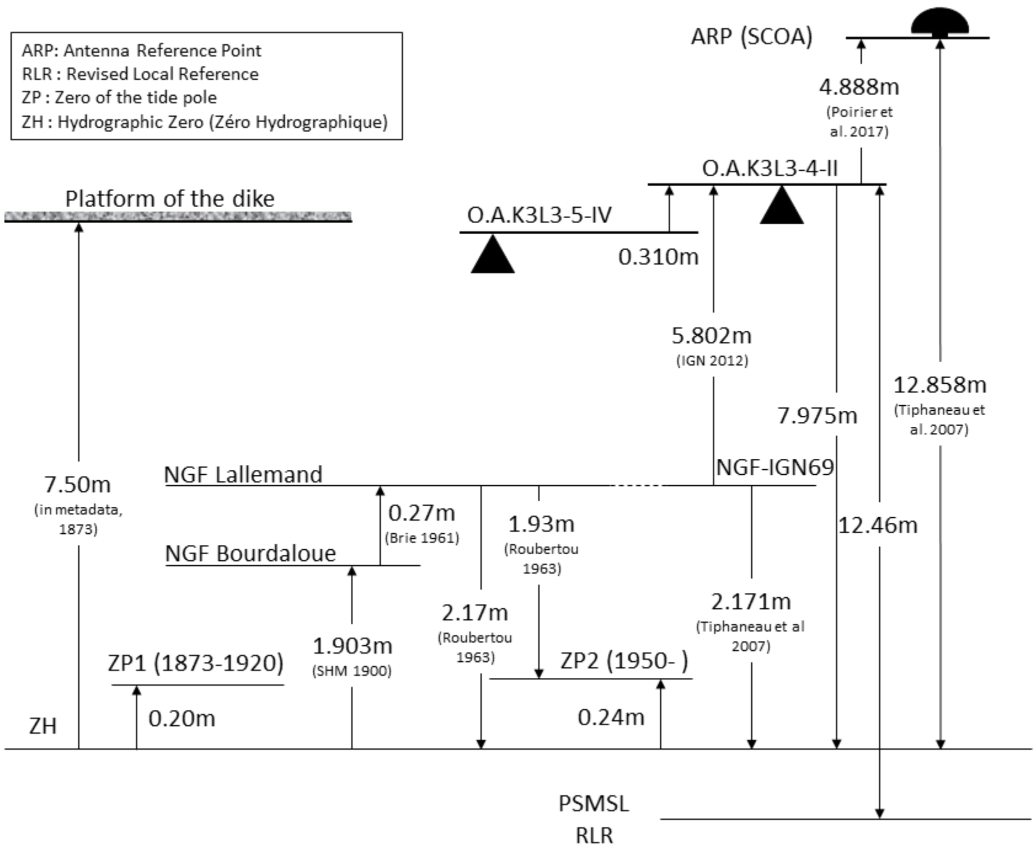

Figure 3: Vertical datum definitions and relationships between benchmarks at Socoa tide gauge. O.A.K3L3-4-II is the primary benchmark, O.A.K3L3-5-IV is the benchmark shown in Figure 1e. The reference to the measurements is given inside parenthesis (in small fonts).

The first levelling related to the tide gauge was performed in 1873, which established the ZH to be 20cm below the zero of the tide pole (ZP), and 7.50m below the dike level (AD64-4S 33 (Pau); SHD Vincennes – DD2-2053). From published document (Annuaire de marées de 1900, Archive Shom), ZH level was reported to be -1.903m relative to the first national levelling and associated datum of France established by Bourdaloue (NGF-Bourdaloue) in 1857-1864. However, it is not clear when this datum connection was made. NGF-Bourdaloue has a difference of 27 cm at Socoa with the second national levelling datum later established by Charles Lallemand during 1880-1922 (NGF-Lallemand), locating the hydrographic zero at -2.17m from the NGF-Lallemand (Brie 1961). No other report of levelling surveys was found during the Chazallon tide gauge period.

In a hydrographic survey done in 1961, the hydrographer indicates a ZH that was 18 cm above the originally established hydrographic zero (Brie 1961). However, it is later noted by a subsequent survey in 1963 that during the survey of 1961, the tide gauge was suffering heavy siltation and blockage of the connection with the sea (Roubertou 1963). The zero of the tide pole was measured at -1.93m NGF Lallemand. It appears that this tide pole is a different from the tide pole during (1873-1920), and the hydrographic zero at 24cm below the zero of the tide pole.

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

In a letter to SHOM, dated 9 October 1968, it is mentioned that "the zero of the tide pole" (zero de l'echelle) is located -2.178m NGF Lallemand, and the primary benchmark is located at 5.822m NGF Lallemand (. This is identified as a mistake based on the survey done in 2007 when the height of OaK3L3-4-II is measured to be 5.805m IGN69 (Tiphaneau et al. 2007). NGF-IGN69 is the current (third) levelling datum established by the Institut National de l'information geographique et forestiere (IGN) over 1962-1969, The hydrographic zero (ZH) is reported to be 7.975m below the OaK3L3-4-II benchmark, and 2.171m below NGF-IGN69 datum (Poirier et al. 2017). It is to be noted here that, the difference between the datum of NGF Lallemand and NGF-IGN69 at Socoa is reported to be 0 m (Grid 1245, https://geodesie.ign.fr/contenu/fichiers/grillesorthonormales/GrilleOrthoNormale_Ouest.pdf, last accessed 19-07-2020). From the available documents, no change in ZH definition is reported.

4 Data quality assessment

In the previous section, we discussed the method used to reduce the records to a common time system, and then analyzed and assessed the continuity of the vertical datum (ZH). Following these two steps provided the initial timeseries, which was then passed through quality assessment to identify incorrect or suspicious values in height and/or time (IOC, 2020). Several methods, described in the following subsections, were used to identify potential problems in the data. Based on rescued metadata, a correction was applied wherever possible, and the corresponding data was flagged.
The flag value is built as a 4-bit number where 1 means the correction is applied and 0 no correction is applied. Each bit from left to right corresponds to the following correction:

- Bit 1 – time correction
- Bit 2 – height correction
- Bit 3 – low confidence in the correction in time or height
- Bit 4 – documented siltation period

For example, the 4-bit flag 1010 reads as follow: A time correction is applied (first bit is 1 = True), without height correction (second bit is 0= False), but the data is suspected to be bad (third bit is 1 = True) even if no siltation was reported (fourth bit is 0 = False). The idea is like the flag provided with the PSMSL data (https://www.psmsl.org/data/obtaining/psmsl.hel).
Two files are provided as supplementary material, listing the corrections done on the raw data, for the ledgers and the charts, respectively. These files are henceforth identified as 'Correction file'. In the following section, the quality control steps, and relevant analysis are discussed.

4.1 Quality control and corrections

Several basic quality control methods based on visual inspection was applied during the time series construction process. For the ledgers, the tabulated values in spreadsheets were colour-coded with the colour range between maximum and minimum

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

value (See Supplementary Figure S5). One of the common errors that this procedure highlights is the wrong transcription of the height by 1m (sometimes 2m). These corrections are flagged as height correction (second bit is 1 in the flag).

Once the basic corrections were applied, a tidal harmonic analysis was performed, and the recorded water levels were compared with the predicted water levels visually week-by-week. This comparison process was useful to identify days with a wrong date (switched with the previous or the following curve in the chart) during transcription, as well as incorrect high and low tides with respect to the tide gauge journal. The tide gauge journal was checked, and corrections were made as appropriate. The high and low tide corrections were typically between 10 and 20 cm.

For the digitized charts, the check sheets accompanying the charts were consulted before the time series extraction using NUNIEAU. Anomalies in time were noted for some charts, where the last time of measurement on the chart was different from the one indicated in the check sheet. This type of anomaly is likely due to the faulty placement of the chart on the rotating drum, causing a time difference for the entire measurement period covered by the chart (typically in the order of 5 minutes). The time information recorded on the check sheets was used to apply a time correction. Whenever a constant difference between the time mentioned in the check sheet and the tide gauge was noted, a time shift was applied to the final dataset. Where the time-shift is different at the beginning and the end, the minimum value of the time-shift was applied to the final data. In some cases, the hourly grid-scale in the charts was relabelled by the observer. The changes induced by grid relabelling were applied directly in the parameterization of NUNIEAU, rather than applying them later.

Some additional issues were noticed during the processing of the charts that could not be corrected, which include occasional slowing down of the clocks, mismatch between the height measured by the chart and the tide-pole reading (reported in the check sheets) and delayed rising or falling tidal curve (Supplementary Figure S6). Furthermore, siltation was noted to be a major problem at this tide gauge station. These issues are addressed in the next section.

The above quality controls resulted in a corrected data set with variable time steps depending on the source (ledgers, charts), which was further decimated to hourly values using a linear interpolation. During interpolation, the missing values were computed only if the interpolated timestamp was surrounded by valid data points. The missing values remained missing.

4.2 Unresolved data quality issues

4.2.1 Slowing-down of the clock

Thanks to the check sheets, the consistency of the clock at the beginning and the end of a recording period of a chart were able to be cross-checked (Supplementary Figure S6). The applicable corrections are applied as described above. However, in some cases, the beginning of the clock was found to be correct with a slow-down at the end. Given the time length of each record in each chart (typically 8-10 days), it is difficult apply a correction confidently. These values are flagged as values with low confidence (third bit in the flag set to 1).

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

4.2.2 Delayed rising/falling curve

In some instances, the position of the floating device seems to have malfunctioned. The associated curves display a quasi-linear rise/fall, instead of the characteristic sinusoidal-like (tidal) evolution (Supplementary Figure S8). In all the cases with such a problem, the tide gauge regains its normal behaviour in the next tidal cycle. The values impacted by this issue are also flagged as potentially bad values (third bit in the flag set to 1).

4.2.3 Siltation

One of the main known issues for the Socoa tide gauge is siltation of the stilling well (Roubertou 1963, Poirier et al. 2017). The geometry of the stilling well is shown in Figure 4a. The stilling well (Figure 4b) is connected through a pipe of 8cm diameter. The first major siltation problem with the data recording was noticed within the first few years of operation (from metadata). Significant maintenance work was undertaken during 1883-1884 to improve the connectivity of the stilling well to the ocean by creating a duct (Figure 4a,d). The entrance shown in Figure 4c,d was apparently open and accessible through a wooden door. At some (unknown) point, the entrance was partially closed, and the connectivity with the stilling well was severed. After starting the reoperation of the tide gauge in 1950, the stilling well exhibited siltation and blockage related problems (Robertou 1963).

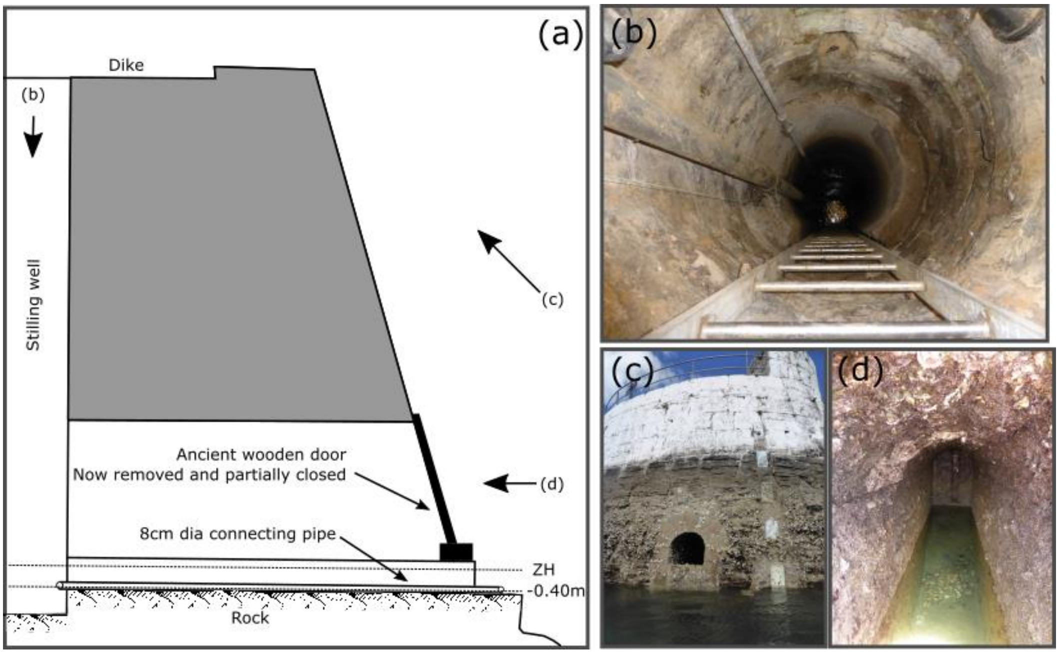

Figure 4: (a) Schematic of the current stilling well. (b) View from above inside the stilling well. (c) Entrance to the stilling well (at about 1m above water level). (d) From the entrance, inside the channel to the stilling well. Images collected during the fieldwork in 2017 (Poirier et al. 2017).

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

Figure 5 shows the M2 amplitude and phase estimates from a running tidal harmonic analysis with yearly segments of water levels recorded at Socoa from 1875 to 2020 using Utide (python) version 0.2.6 (Codiga 2011, https://github.com/wesleybowman/UTide). The error bars in the figure represents the 95% confidence interval.

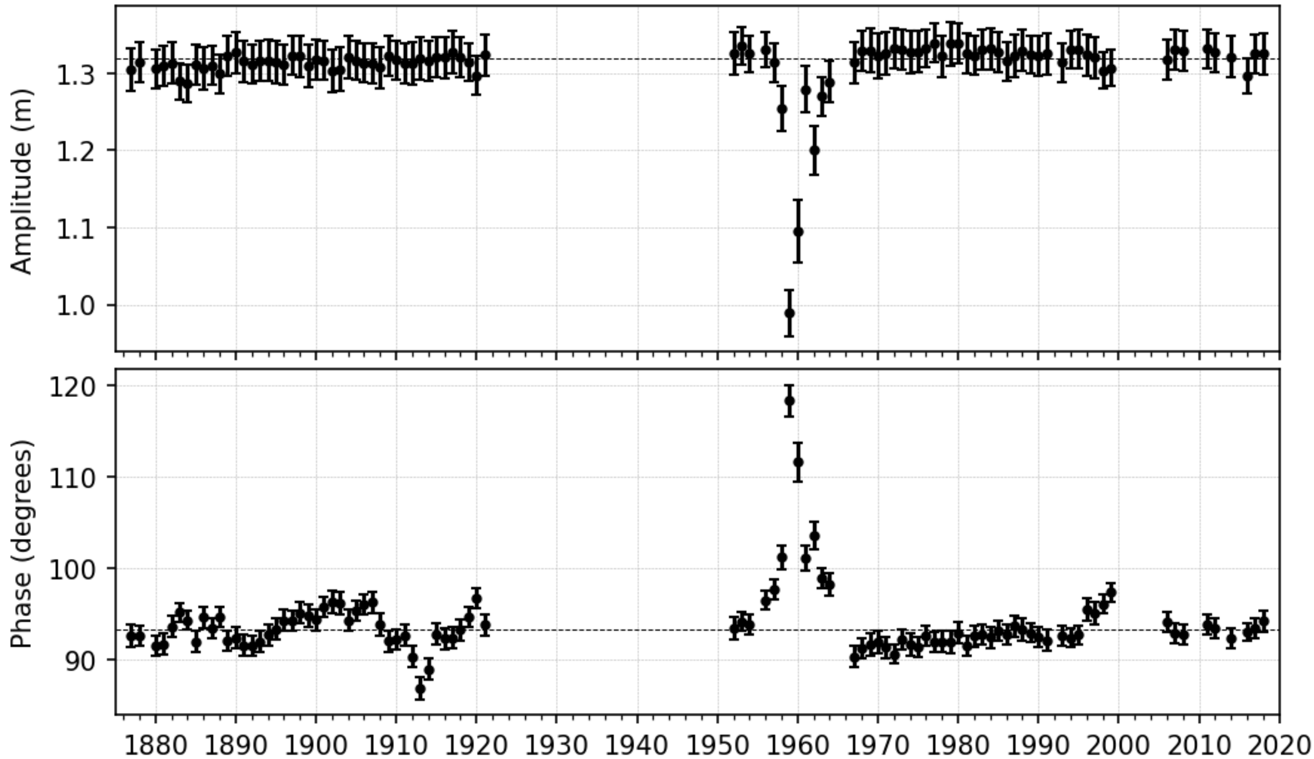

Figure 5: M2 amplitude (top) and phase (bottom) calculated for one-year segments using tidal harmonic analysis. The dotted lines correspond to the amplitude and phase computed for the whole timeseries. Error bars are 95% confidence intervals.

As noted in the literature (e.g. Pugh and Woodworth 2014), malfunctioning of the instrument can be detected by examining the tidal constituents. More specifically, siltation inside the stilling well can be detected as a simultaneous amplitude attenuation and phase delay (e.g., Wöppelmann et al. 2014). The most apparent siltation problem can be observed during 1956-1963 in Figure 5, which is supported by the report of hydrographic surveys carried out at that time (Robertou 1963). Another simultaneous amplitude attenuation and phase delay can also be spotted around end of 1990s (1996-2000).

4.3 Buddy checking

One of the commonly used quality control techniques of sea level records is the so-called 'buddy checking', which relies on mean sea level timeseries from nearby sites (Pugh and Woodworth, 2014). The difference with nearby sea level records essentially removes the common part of spatially coherent modes of variability and can reveal malfunctioning at one of the gauges – for instance, step-like features associated with vertical datum discontinuity (Woodworth 2003). Here, we compare our record with the sea level record from Brest (obtained from https://data.shom.fr), and Santander (obtained from PSMSL,

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

Earth System Science Data
Open Access
Discussions

https://www.psmsl.org/) tide gauge. Brest tide gauge data is one of the well-validated long timeseries (starting from 17th century) in this region (Woppelmann et al. 2006a, 2008) covering the whole timeseries of Socoa.

We adopted the PSMSL processing scheme for computing the monthly for Socoa and Brest. First, a Demeriliac filter is applied on the hourly data to obtain a detided hourly timeseries for Socoa and Brest. From the hourly detided water level, the daily mean sea level was obtained using daily average. A monthly mean is computed only if 50% or more data is available. As the Santander dataset is directly obtained from PSMSL, no further pre-processing was necessary.

The differences of monthly mean sea level at Socoa with Brest and Santander are shown in Figure 6. For comparison, the mean (computed over 1965-2000) was removed from each dataset before computing the difference. Note that the periods with suspected siltation issues (Section 4.2.3) were previously removed from Socoa timeseries.

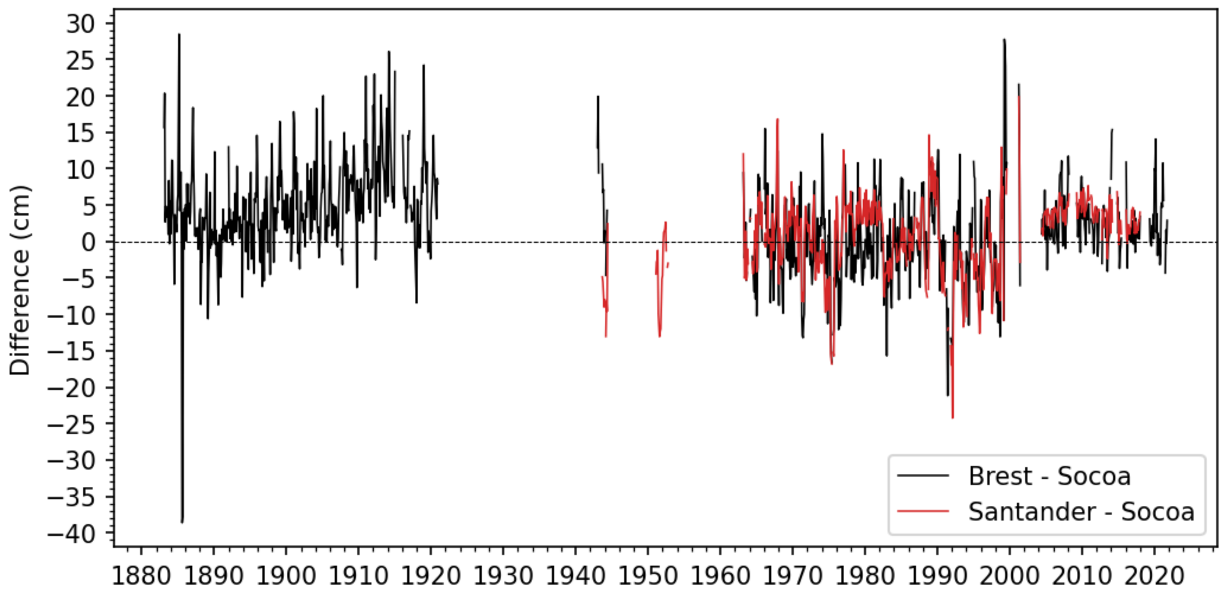

Figure 6: Buddy checking for Socoa by differencing from Brest (black) and Santander (red) through monthly mean sea level records.

From Figure 6, no persistent step-like feature is seen in the Brest minus Socoa timeseries (black), which further strengthen our confidence on the vertical datum continuity established in Section 3.3. In Figure 6, it is interesting to note the gradually increasing difference during the early 20th century. In literature, this decadal feature is shown to be linked to a large-scale sea-level variability coherent with atmospheric modes of the North Atlantic (Sturges and Douglas 2011, Calafat et al. 2012, Chafik et al. 2019), and explained by the steric response (Calafat et al. 2012). Both Brest and Socoa tide gauge shows this decadal variability (see Supplementary Figure S9), with lower amplitude at Socoa compared to Brest. Hence producing the increasing positive difference from 1900 to 1915 in Figure 6.

The Santander minus Socoa timeseries also does not indicate any datum shift, and typically consistent with the Brest minus Socoa timeseries. However, in the Santander minus Socoa timeseries (red), we see a jump during (1976-1980), indicating a potential shift of 5 cm during that time at Santander. Recently, Marcos et al. (2021) extended Santander timeseries through data archaeology back to 1875 (see Supplementary Figure S9). However, there are multiple apparent da tum shifts in the data during the early years (1875-1910), thus we refrained from including the extended timeseries in the buddy checking for Socoa.

5. Trend analysis

The trends estimates and associated error bars at Socoa and Brest for selective time periods are shown in Table 2. Over the same period (1900-2018), for Brest the trend is 1.42+-0.07 mm/year, for Socoa 1.92+-0.08 mm/year. The benefit of a long timeseries is clear here – longer the timeseries, tighter the error bar. To compare with previously published result by Marcos et al. (2021), we also computed the trend for the non-detided timeseries shown in Supplementary Figure S9, listed in Table 2 under common period with asterisk (*). Between Socoa and Santander, the trend estimate is very close for the common period, 2.08±0.20 mm/year for Socoa, and 2.01±0.12 mm/year for Santander.

We also analysed for inflexion point in trend at Socoa. The analysis is motivated by Wöppelmann et al. (2006a) who noted an inflexion point around 1890 at Brest, which is close to the inflexion point estimated for Liverpool around 1880 by Woodworth (1999). With a running window of 20 years, we confirm an inflexion point at 1887 for Brest. With the same analysis procedure, for Socoa, we estimate an inflexion point between 1895-1900 (see Supplementary Figure 10).

Table 2. Estimated linear trends in mm/year at Brest and Socoa over various time periods.

Period	Brest	Socoa	Santander
Available	1.30±0.06	1.96±0.08	-
Common (1900-2018)	1.50±0.09	2.12±0.11	-
	1.49±0.09*	2.08±0.11*	2.01±0.12*
Chazallon era (1876-1920)	1.00±0.48	0.82±0.37	-
Brillie era (1963-1997)	1.78±0.52	1.95±0.61	1.44±0.70

* Computed from annual mean sea level without filtering the tide.

6 Data availability

The raw water level timeseries dataset derived from the data digitization, the processed dataset, associated metadata, and python notebooks for processing the data is available openly at https://doi.org/10.5281/zenodo.7438469 (Khan et al. 2022). An continuously updated timeseries of the Socoa sea level can be obtained from the Shom portal (http://dx.doi.org/10.17183/REFMAR#95).

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

7 Conclusions

Through a thorough archival research, data-rescue, digitization, and metadata analysis, we have increased the coverage of the existing hourly sea level record at Socoa, Saint-Jean-de-Luz (France) by about 40 years. This extended dataset will be communicated and deposited at international sea level databanks to further increase the number of long-term sea level records extending back into the 19th century. One of the major features of this sea level record is its location, which has remained the very same (peer and stilling well) since its installation in 1875. During archival and data analysis we have noted a recurrent problem of siltation in the stilling well. In this paper, we have tried our best to document such problems and flag the associated data. Besides the final sea level dataset, we provide the raw data, associated corrections, computational environment, and notebook as companion data. The objective of this is to promote reproducible research and to increase transparency by allowing validation of our computations without considerable effort by interested parties.

We have noted unrecoverable deterioration of historical paper documents during our data rescue operations. This underlines the importance of this type of data archaeological exercise. Similarly, relevant metadata are also in the same danger of being lost. Analysing the history of individual tide gauges can reveal important location-specific issues, like siltation, that might not be directly evident from the global dataset at this moment.

The data recovered and rescued in this work would be useful for long-term sea level trend analysis (e.g., Gehrels and Woodworth, 2013) and modelling at decadal to interannual scale (e.g., Calafat et al. 2012, Ding et al. 2021). Investigation into the extreme events will specially benefit from the hourly (or shorter) temporal sampling of the extended timeseries.

Finally, as indicated by Pouvreau (2008), there are many more stations in France where the existing sea level record could be extended. We hope that this rescue and sea level data archaeology exercise will encourage to undertake similar efforts at an even larger scale than France.

Author contribution

LT, GW, and AL conceived the idea of the data archaeology for Socoa (Saint Jean-de-Luz) and secured the funding. IB did the data cataloguing, rescue, and digitization under supervision of AL and NP. JK analysed the data, developed the computational notebooks, and associated figures, curated the data for publishing, and wrote the first draft of the manuscript. GW and LT produced the second draft of the manuscript. All co-authors contributed to editing of the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

The authors wish to thank Mr. Alain Roudil and Mr. Christian Ondicola for providing valuable information regarding the history of the tide gauge. We acknowledge Dr. Marta Marcos, University of the Balearic Islands, for providing the monthly mean sea level data for Santander station. We also acknowledge PSMSL for their long-standing effort to maintain a global sea-level databank. The work presented here was carried out within the framework of the FEDER-FSE "Aquitaine" 2014-654, 2020 project EZPONDA (grant No 2018-4619910).

References

Aarup, T., Wöppelmann, G., Woodworth, P.L., Hernandez, F., Vanhoorne, B., Schöne, T., and Thompson, P.R.: Comments on the article "Uncertainty and bias in electronic tide-gauge records: evidence from collocated sensors" by S. Pytharouli, S. Chaikalis, S.C. Stiros in Measurement (Vol. 125, September 2018), 2019.

Arnoux, F., Abadie, S., Bertin, X. and Kojadinovic, I.: Coastal flooding event definition based on damages: Case study of Biarritz Grande Plage on the French Basque coast. Coastal Engineering, 166, p.103873, doi: 10.1016/j.coastaleng.2021.103873, 2021.

Arns, A., Wahl, T., Wolff, C., Vafeidis, A.T., Haigh, I.D., Woodworth, P., Niehüser, S. and Jensen, J.: Non-linear interaction modulates global extreme sea levels, coastal flood exposure, and impacts. Nature communications, 11(1), pp.1-9, doi: 10.1038/s41467-020-15752-5, 2020.

Bradshaw, E., Lesley, R., and Thorkild, A. : Sea Level Data Archaeology and the Global Sea Level Observing System (GLOSS), Geo. Res. J., 6, 9-16, doi :10.1016/j.grj.2015.02.005, 2015.

Brie: Report no. 158. Mission hydrographique de France et d'Algerie (MHCFA), Cherbourg, 1961.

Bureau des longitudes: Guide de données astronomiques pour l'observation du ciel: Annuaire du Bureau des longitudes, IMCEE and Bureau des longitudes, pp. 56-58, ISBN: 9782759805419, 2011. (Retrieved from https://gallica.bnf.fr/ark:/12148/bpt6k9614055r)

Calafat, F. M., Chambers, D. P., and Tsimplis M. N.: Mechanisms of Decadal Sea Level Variability in the Eastern North Atlantic and the Mediterranean Sea, Journal of Geophysical Research: Oceans, 9, n/a–n/a. doi:10.1029/2012jc008285, 2012.

Chafik, L., Nilsen, J.E.Ø., Dangendorf, S., Reverdin, G. and Frederikse, T.:North Atlantic Ocean circulation and decadal sea level change during the altimetry era. Scientific reports, 9(1), pp.1-9, doi: 10.1038/s41598-018-37603-6, 2019.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

https://doi.org/10.5194/essd-2022-443
Preprint. Discussion started: 17 January 2023

Codiga, D.L.: Unified Tidal Analysis and Prediction Using the UTide Matlab Functions. Technical Report 2011-01. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 59pp. url: ftp://www.po.gso.uri.edu/pub/downloads/codiga/pubs/2011Codiga-UTide-Report.pdf, 2011.

Colosi, J. A., and Walter, M.: Tales of the Venerable Honolulu Tide Gauge, Journal of Physical Oceanography, 6, 967–996, doi:10.1175/jpo2876.1, 2006.

Dangendorf, S., Marcos, M., Wöppelmann, G., Conrad, C.P., Frederikse, T. and Riva, R.: Reassessment of 20th century global mean sea level rise. Proceedings of the National Academy of Sciences, 114(23), pp.5946-5951, doi: 10.1073/pnas.1616007114, 2017.

Ding, H., Jin, T., Li, J. and Jiang, W.: The Contribution of a Newly Unraveled 64 Years Common Oscillation on the Estimate of Present-Day Global Mean Sea Level Rise. Journal of Geophysical Research: Solid Earth, 126(8), doi: 10.1029/2021JB022147, 2021.

Dodet, G., Bertin, X., Bouchette, F., Gravelle, M., Testut, L. and Woppelmann, G.: Characterization of sea-level variations along the Metropolitan Coasts of France: waves, tides, storm surges and long-term changes. Journal of Coastal Research, 88(SI), pp.10-24, doi: 10.2112/SI88-003.1, 2019.

Ekman, M.: Climate Changes Detected Through the Worlds Longest Sea Level Series, Global and Planetary Change, 9, 215–224, doi:10.1016/s0921-8181(99)00045-4, 1999.

Gouriou, T., Míguez, B.M. and Wöppelmann, G.: Reconstruction of a two-century long sea level record for the Pertuis d'Antioche (France), Continental Shelf Research, 61, pp.31-40. doi:10.1016/j.csr.2013.04.028, 2013.

Gehrels, W.R. and Woodworth, P.L.: When did modern rates of sea-level rise start?, Global and Planetary Change, 100, pp.263-277, doi:10.1016/j.gloplacha.2012.10.020 2013.

Hogarth, P., Hughes, C.W., Williams, S.D.P., and Wilson, C.: Improved and Extended Tide Gauge Records for the British Isles Leading to More Consistent Estimates of Sea Level Rise and Acceleration Since 1958, Progress in Oceanography, 5, doi:10.1016/j.pocean.2020.102333, 2020.

Hunter, J., Coleman, R., and Pugh, D.: The Sea Level at Port Arthur, Tasmania, from 1841 to the Present. Geophysical Research Letters, 4, doi:10.1029/2002gl016813, 2003.

IOC: Quality control of in situ sea level observations: a review and progress towards automated quality control, IOC Manuals and Guides, No. 83, UNESCO, Paris, https://unesdoc.unesco.org/ark:/48223/pf0000373566, 2020.

IOC: Manual on sea level measurement and interpretation, Volume I – Basic Procedures, IOC Manuals and Guides, No. 14, UNESCO, Paris, 1985.

Khan, M.J.U., Van Den Beld, I., Woppelmann, G., Testut, L., Latapy, A., & Pouvreau, N.,: Sea level data archaeology at Socoa (Saint Jean-de-Luz, France) (v1.0) [Data set]. Zenodo, doi:10.5281/zenodo.7438470, 2022.

Letetrel, C., Marcos, M., Míguez, B. M., and Woppelmann, G.: Sea Level Extremes in Marseille (NW Mediterranean) During 1885-2008, Continental Shelf Research, 7, 1267–1274, doi:10.1016/j.csr.2010.04.003, 2010.

Marcos, M., Puyol, B., Amores, Gómez, B. P., Fraile, M., and Talke, S. A.: Historical Tide Gauge Sea-Level Observations in Alicante and Santander (Spain) Since the Century, Geoscience Data Journal, 1, doi:10.1002/gdj3.112, 2021.

Marcos, M., Puyol, B., Wöppelmann, G., Herrero, C., and García-Fernández, M. J.: The Long Sea Level Record at Cadiz (Southern Spain) from 1880 to 2009, Journal of Geophysical Research, 12, doi:10.1029/2011jc007558, 2011.

Marcos, M., Calafat, F.M., Berihuete, Á. and Dangendorf, S.: Long-term variations in global sea level extremes. Journal of Geophysical Research: Oceans, 120(12), pp.8115-8134, 2015.

Martin Miguez, B., Le Roy, R., and Wöppelmann, G.: The use of radar tide gauges to measure variations in sea level along the French coast, Journal of Coastal Research, 24, 61-68, doi: 10.2112/06-0787.1, 2008.

Muis, S., Verlaan, M., Winsemius, H.C., Aerts, J.C. and Ward, P.J.: A global reanalysis of storm surges and extreme sea levels. Nature communications, 7(1), pp.1-12, doi: 10.1038/ncomms11969, 2016.

Müller, M.: Equation of time-problem in astronomy. ACTA PHYSICA POLONICA SERIES A, 88, pp.S-49.Vancouver, 1995.

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. CifuentesJara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)], 2019.

Pan, H. and Lv, X.: Is there a quasi 60-year oscillation in global tides?. Continental Shelf Research, 222, doi: 10.1016/j.csr.2021.104433, 2021.

Piccioni, G., Dettmering, D., Bosch, W. and Seitz, F.: TICON: TIdal CONstants based on GESLA sea-level records from globally located tide gauges. Geoscience Data Journal, 6(2), pp.97-104, doi: 10.1002/gdj3.72, 2019.

Poirier, E., Gravelle, M., and Wöppelmann, G.: Contrôles du marégraphe de Socoa (Saint Jean-de-Luz) – Missions du 10-12 mai 2017 et du 23-24 août 2017, SONEL Rapport Nr. 001/17, 2017.

Pouvreau, N.: Trois Cents Ans de Mesures Marégraphiques En France: outils, Méthodes Et Tendances Des Composantes Du Niveau de La Mer Au Port de Brest, PhDThesis, Université de La Rochelle, 2008.

Pouvreau, N., Miguez, B. M., Simon, B., and Wöppelmann, G.: Evolution of the semi-diurnal tidal constituent M2 at Brest from 1846 to 2005, Comptes Rendus Geoscience, 11, 802–808, doi:10.1016/j.crte.2006.07.003, 2006.

Poulle, Y.: La France à l'heure allemande. In: Charter School Library, volume 157, issue 2. pp. 493-502, doi:10.3406/bec.1999.450989, 1999.

Pugh, D., and Woodworth, P.: Sea-Level Science: Understanding Tides, Surges, Tsunamis and Mean Sea-Level Changes, Cambridge University Press, 2014.

Rasmussen, D.J., Bittermann, K., Buchanan, M.K., Kulp, S., Strauss, B.H., Kopp, R.E. and Oppenheimer, M.: Extreme sea level implications of 1.5 C, 2.0 C, and 2.5 C temperature stabilization targets in the 21st and 22nd centuries. Environmental Research Letters, 13(3), p.034040, doi: 10.1088/1748-9326/aaac87, 2018.

Roubertou, A.: The Brillié Tide-Gauge, The International Hydrographic Review, Reproduced from the “Bulletin d ’information du Comite Central d ’Oceanographie et d’Etude des Cotes (C.O.E.C.), 7th year, No. 6, Paris, June 1955”, 1955.

Roubertou, A.: Rapport no. 272. Mission Hydrographique de Dragage (MHD). Bordeaux, 1963.

Sturges, W. and Douglas, B.C.: Wind effects on estimates of sea level rise. Journal of Geophysical Research: Oceans, 116(C6), doi: 10.1029/2010JC006492, 2011.

SHOM: Références altimétriques maritimes (RAM), Shom, Brest, France, url: https://diffusion.shom.fr/pro/references-altimetriques-maritimes-ram.html, 2020 (last accessed: 25/03/2022).

Tadesse, M., Wahl, T. and Cid, A.: Data-driven modeling of global storm surges. Frontiers in Marine Science, 7, p.260, doi: 10.3389/fmars.2020.00260, 2020.

Talke, S.A., Orton, P. and Jay, D.A.: Increasing storm tides in New York harbor, 1844–2013. Geophysical Research Letters, 41(9), pp.3149-3155, doi: 10.1002/2014GL059574, 2014.

Talke, S.A., Kemp, A.C. and Woodruff, J.: Relative sea level, tides, and extreme water levels in Boston Harbor from 1825 to 2018. Journal of Geophysical Research: Oceans, 123(6), pp.3895-3914, doi: 10.1029/2017JC013645, 2018.

Testut, L., Miguez, B. M., Wöppelmann, G., Tiphaneau, P., Pouvreau, N., and Karpytchev., M.: Sea Level at Saint Paul Island, Southern Indian Ocean, from 1874 to the Present, Journal of Geophysical Research, 12, doi:10.1029/2010jc006404, 2010.

Tiphaneau, P., Breilh, J.-F., & Wöppelmann, G.:Contrôle des performances du marégraphe radar BM70A de Socoa (Saint Jean-de-Luz), Report No. 002/07, May, Centre littoral de Geophysique - Université de la Rochelle, La Rochelle, url: https://www.sonel.org/SoTaBord/ged/Tiphaneau-2007-controle_des_performances_du_m.pdf, 2007.

Ullmann, A., Pons, F., Moron, V.: Tool kit helps digitize tide gauge records, EOS Trans. AGU, 86(38), doi: 10.1029/2005EO380004, 2011.

Woodworth, P. L.: High Waters at Liverpool Since 1768: the UKs Longest Sea Level Record, Geophysical Research Letters, 6, 1589–1592, doi:10.1029/1999gl900323, 1999.

Woodworth, P.L., Hunter, J.R., Marcos, M., Caldwell, P., Menéndez, M. and Haigh, I.: Towards a global higher-frequency sea level dataset. Geoscience Data Journal, 3(2), pp.50-59, doi: 10.1002/gdj3.42, 2016.

Wöppelmann, G., Marcos, M., Coulomb, A., Míguez, B. M., Bonnetain, P., Boucher, C., Gravelle, M., Simon, B., and Tiphaneau, P.: Rescue of the Historical Sea Level Record of Marseille (France) from 1885 to 1988 and Its Extension Back to 1849-1851, Journal of Geodesy, 6, 869–885, doi:10.1007/s00190-014-0728-6, 2014.

Wöppelmann, G., Pouvreau, N., and Simon, B.: Brest Sea Level Record: a Time Series Construction Back to the Early Eighteenth Century, Ocean Dynamics, 3, 487–497, doi:10.1007/s10236-005-0044-z, 2006a.

Wöppelmann, G., Zerbini, S., Marcos, and Marcos, M.: Tide gauges and Geodesy: a secular synergy illustrated by three present-day case studies, C. R. Geoscience, 338, 980–991, doi:10.1016/j.crte.2006.07.006, 2006b.

Wöppelmann, G., Pouvreau, N., Coulomb, A., Simon, B. and Woodworth, P.L.: Tide gauge datum continuity at Brest since 1711: France's longest sea-level record. Geophysical Research Letters, 35(22), doi: 10.1029/2008GL035783, 2008.