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

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Abstract. In this data paper, the sea level time series at Socoa (Saint Jean-de-Luz, Southwestern France) has been~~is~~ extended ~~in a~~through a data archaeology exercise. We conducted a comprehensive research of national and local archives to catalogue water level records stored in ~~have catalogued water level records stored in~~ ledgers (handwritten record books) and charts (marigrams from mechanical float gauge), ~~as well as~~along with other associated documents (metadata) ~~in thorough research of national and local archives~~. A dedicated ~~n extensive~~ effort was undertaken to ~~made to~~ preserve~~rescue~~ more than 2000~~these~~ documents by archiving them in digital formats. The Socoa time series has been extended back to 1875, with more than 58 station-year of additional data, using this large set of rescued documents. The final time series has hourly sampling, while the raw dataset has finer sampling frequency up to 5 minutes. By analysing ~~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, we assessed the continuity of the vertical datum ~~reveals that the datum of the tide gauge site has been stable~~. We also compared the new~~We assessed the consistency of this new~~ century-long time series to nearby ~~based on nearby~~ tide gauge data to ensure its datum consistency. ~~Although~~ While the overall quality of the time series is generally good~~consistent~~, siltation of the stilling well has occasionally affected certain parts of the record. We have successfully identified these impacted periods and flagged the corresponding data as doubtful~~is found to be a recurrent problem of the stilling well which impacted some part of the extended data.~~. This extended high resolution sea level time series at Socoa, spanning over more than 100 years, will be ~~However, being a high temporal resolution sea level time series spanning more than 100 years, this new dataset will be~~ valuable~~useful~~ for advancing climate research, particularly in studying the decadal scale variations in the North Atlantic, and investigating ~~, as well as~~ the storminess and extreme events along the French Basque coast~~al region~~.

1 Introduction

~~Sea level~~Tide gauge records are ~~one of~~among the oldest instrumental datasets.~~records~~ T~~t~~hey~~at~~ have a crucial contribution to our understanding of contemporary sea level variability and climate change (Ekman 1999, Church et al. 2013). Between 1901 and 2010, ~~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 t~~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 the 19th and 20th century (which provides a baseline for assessing the changes in the 21st century) relies ~~heavily~~ on ~~sparsely located~~ long-term ~~in situ~~ tide gauge ~~datasets~~ records (~~e.g.~~e.g., Dangendorf et al. 2017). A subset of these long time series has beco~~a~~me accessible ~~for~~ to the scientific community through the process of discovery, digitiz~~z~~ation~~,~~ and reconstruction, ~~of a new or extended sea level timeseries from archival records —~~ a procedure which is known as sea level data archaeology (Woodworth~~,~~ 1999, UNESCO/IOC 2020). Over the last few decades, d~~D~~ata archaeology has been applied to different ~~over~~ part of the globe to construct and study long-term sea level variability and change (e.g., Woodworth 1999, Hunter et al. 2003, Woodworth et al. 2010a, Talke et al. 2018). For instance, Woodworth (1999) recovered and analysed the mean high-water level recorded at Liverpool starting from 1768. Similarly, ~~Woppelmann~~Wöppelmann 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~~Wöppelmann 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. Combined~~ing~~ with recent measurements they revealed a statistically zero relative sea level trend. Similarly, Hunter et al. (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 time series for sea level trend analysis (Marcos et al. 2011; 2021; Woodworth, 1999), ~~. –~~w~~W~~hereas, 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 over 1958 to 2018, 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.~~ In long term, tide has also been through changes – which requires high-frequency (typically hourly or less) data to analyse ~~GMSL rise also raises questions regarding associated long-term changes in tide, which requires high frequency sea level observations~~(Woodworth, 2010b, Haigh et al. 2020). ~~-~~During the first half of the 19th century~~,~~ automatic mechanical tide gauges started appearing, paving the ~~path~~ way for systematic continuous measurements of water levels at high frequency (~~Woppelmann~~Wöppelmann et al 2006b). Taking advantage of the archaeology of such high-frequency long-term sea level records, Pouvreau et al. (2006~~8~~) ~~analyzed~~analysed the secular trend in the evolution of M2 (the main lunar semidiurnal tide)~~evolution~~ at Brest. They reported no significant trend but long-period oscillations with 141 years period. Recent research on the tidal change shows that the long-term changes are not linear (Ray and Talke 2019). Pan and Lv (2021) reported a quasi 60-year oscillation in the global tide from a global set of long high-resolution sea level time series. These non-linear changes are sometimes with break points around late 19th century (Pineau-Guillou et al. 2021). These contemporary results further highlight the necessity for long high frequency sea level time series for studying the evolution of tide.~~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~~High frequency~~-resolution~~ past tide gauge time ~~series~~series are 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). Dedicated studies have been conducted to understand the dynamics and the drivers of ESL at local (Letetrel et al. 2010, Talke et al. 2014, Talke et al. 2018), regional (Wahl and Chambers 2015, Marcos et al. 2015, Marcos and Woodworth 2017), and global scales (Menéndez and Woodworth 2010). Among various factors, sea level rise is shown to be the first order driver of the observed ESL change in most of the coastline (Menéndez and Woodworth 2010) and projected to be the major factor for future ESL changes globally (Muis et al. 2016, Fox-Kemper et al. 2021). However, ESL variability also varies regionally depending on the local and regional processes (Menéndez and Woodworth 2010). Long high-resolution sea-level time series are particularly interesting to unravel the contribution from mean sea level change (Letetrel et al. 2010), seasonal and decadal variability (Menéndez and Woodworth 2010, Marcos et al. 2015), and local changes (Talke et al. 2014, Talke et al. 2018). Indeed, it is 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 (Oppenheimer et al. 2019). Such monitoring requires reliable long high-resolution observations. A long time series provides an additional benefit by reducing the uncertainty of ESL analysis (Coles 2001), which equates to better flood risk assessment.

Global high-resolution dataset, like GESLA (Global Extreme Sea Level Analysis; Woodworth 2016, Haigh et al. 2020) has been instrumental for the current global, as well as regional scale studies on ESL. Such a dataset also allowed global and regional analysis of tide (Piccioni et al. 2019), the non-linearity of tide-surge interaction (Arns et al. 2020), as well as data driven modelling of surge (Tadesse et al. 2020). Yet, most of the stations in GESLA have a time series less than 50-year long. As demonstrated by previous studies (Wöppelmann et al. 2014, Talke et al. 2014, 2018, Talke and Jay 2017), data archaeology offers a solution to this scarcity of long-term data by tapping into the potential of rescuing numerous instrumental records worldwide (Bradshaw et al. 2015).~~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 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).~~

As a response to this~~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~~presents a data rescue and archaeology effort to make available a high temporal resolution long-term sea level time series at Socoa. ~~Socoa is~~The tide gauge ~~located~~ is located in~~n~~ 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 1a). The ~~surrounding~~ region is dominated by ~~a~~ strong tides (meso-tidal) and energetic waves (Dodet et al. 2019), making it an important observation location.~~.~~ 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). The data is available at hourly sampling before 2011, and afterwards both the high-frequency (1min) and the hourly data is available.

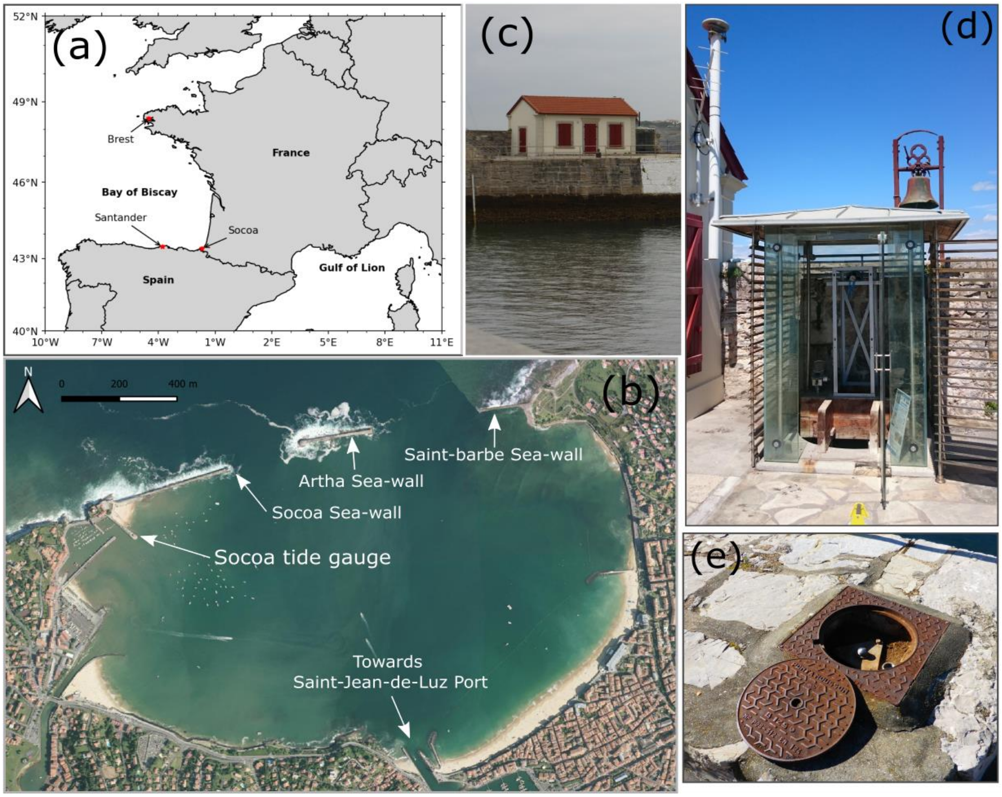


Figure 1~~1~~: (a) Study area indicating the location of the Socoa tide gauge and other tide gauges used in this study (b) The satellite view of the study area (source: IGN geoservices, https://geoservices.ign.fr/). (c) A view of the tide gauge surroundings and the housing

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. The photos in panels c, d, e are provided by SONEL (https://www.sonel.org/).

First, ~~In Section 2 of this paper,~~ the history of the Socoa tide gauge is presented ~~presented and the~~through various instrumentation periods and a summary ~~list~~ of the rescued documents (containing data and metadata) are discussed in Section 2. 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~~ assessment in Section 4. In Section 5, we present a trend analysis.~~.~~ The data availability is detailed in Section 6 with concluding remarks in Section 7~~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 (Figure 1c) with an adjacent stilling-well system (Figure 1d) 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 Martí~~i~~n Mí~~i~~guez et al. 2008). In the~~The description of each instrumentation period is provided in the~~ following sub-sections, we provide descriptions of each instrumentation period, along with detailed information about the data and the metadata. ~~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. Like most of the~~Typical to~~ float ~~tide~~ gauges, the displacement~~s~~ of the float ~~by the change in water level~~ is reduced through a mechanical system ~~means (reducer)~~ and the resulting sea level variation is recorded ~~i~~on a ~~time-controlled rolling~~ paper ~~(called~~ chart~~)~~ controlled by a clock (IOC 1985). One of the Chazallon type tide gauges was installed in La Rochelle (Vieux Port) and operated from 1863 to 1874 (Gouriou et al. 2013). This tide gauge was then transferred to the Socoa ~~station~~ in 1875. At Socoa, the float of the tide gauge was installed in~~to~~ a stilling well~~,~~ located ~~just~~ near ~~by~~ the housing ~~where the device was installed~~. The 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/).

Two types of historical ~~water level~~ records ~~are~~ have been 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~~with water

level values~~s~~ obtained by inspection of the charts by an operator~~done by an observer from the original charts~~. The ledgers (Supplementary Figure S1) and charts are currently 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 Temporary tide gauge during World War II period: (1942 to 1944)

In the currently available archives, e.g., Shom, or Permanent Service for Mean Sea Level (PSMSL, Holgate et al. 2013), 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 any tide gauge operating at Socoa. After inspection, we found a different paper size of these charts compared to Chazallon or Brillie, 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 the Germans, on the other side of the Socoa bay. The data during WWII appears to be consistent with the rest of the record, as confirmed by a tidal analysis. No record was found between this German tide gauge (1944) and the Brillie tide gauge (1950).

2.3~~2~~ The Brillie tide gauge period: 1950 to 2004

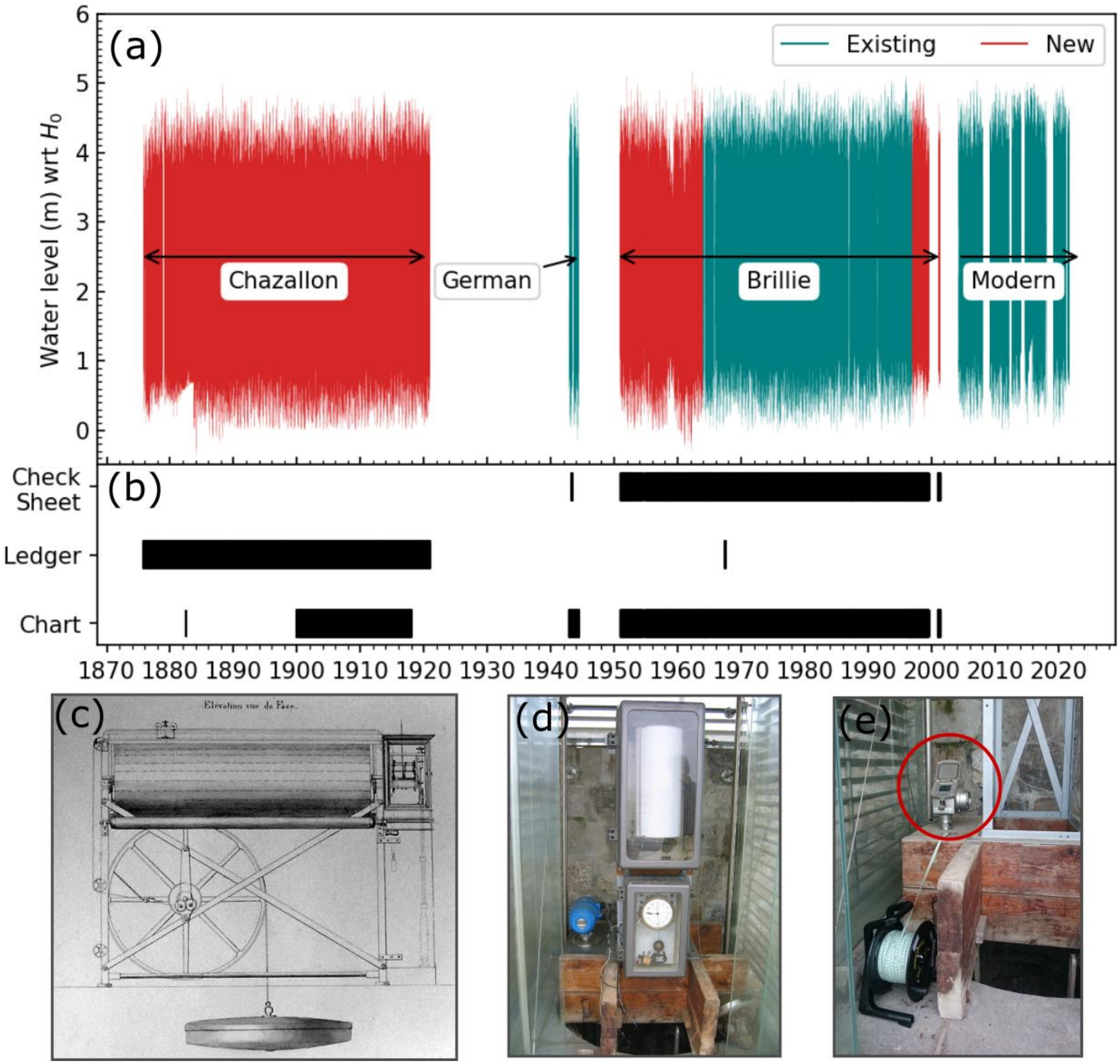
During 1950, a Brillie type float ~~tide~~ gauge (large model type, Robertou 1955) was installed (Figure 2d) in the ~~former~~ stilling well built for Chazallon gauge. Each chart of~~for~~ this large ~~type~~ model type is ~~of~~ 72x50 cm in dimension (x-y). The x-axis of the paper is divided into 24 divisions (corresponding to each hour), and each hourly division is further subdivided into 10-minute subdivisions. On the y-axis~~other hand, with~~ there is a 1/10 reduction in the water level variation, i.e., the y-axis represents a range of 5m in sea level (50cm x 10). There are further subdivisions on the charts of ~~height and are divided into~~ 25cm ~~with a subdivision of~~ and 5cm. Surprisingly, n~~N~~o documentation was ~~recovered~~ found ~~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 starts in December 1950. In total, 2477 charts spanning the period December 1950 to 2001 were recovered from the local archive - Archives des Pyrénées-Atlantiques at Bayonne~~(henceforth AD64, http://archives.le64.fr/)~~. No data were found for 2002-2003. The ~~recording of~~ water level curves ~~in~~ on the charts during the Brillie ~~tide gauge~~ period were~~as done~~recorded in the legal time of France (~~See~~ see Section 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~~ on 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~~charts and 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).~~

2.4~~3~~ The modern instrumentation: 2004 to ongoing

With the advent of the modern RONIM (Réseau d'Observation du Niveau des Mers) sea level measurement network (Martín Míguez et al. 2008~~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~~1d. This tide gauge is currently 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~~ in both raw and post-processed quality-controlled form~~data)~~. Raw data is sampled at 1-minute. Data from ~~The~~ the tide gauge is ~~equipped with, and~~ accessible through the Global Telecommunication System~~s~~ (GTS) network, which enables a real-time data ~~flux~~flow. This data ~~flux~~ flow enables real-time monitoring of the gauge, for instance via the Intergovernmental Oceanographic Commission (IOC) ~~sea~~ Sea ~~level~~ Level ~~monitoring~~ Monitoring ~~facility~~ Facility (see http://www.ioc-sealevelmonitoring.org/station.php?code=scoa2). Note that the data from the IOC ~~facility~~ Facility should not generally be used for any scientific ~~high-precision~~ application, as its main design and procedures have been designed for monitoring the operational status of the gauges (Aarup et al. 2019).

It is worth ~~noteworthy~~ noting here that at Socoa~~,~~ the position of the tide gauge ~~remains~~ remained the same over its full period of observation from November 1875 until now through the 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~~ a caveat ~~of~~ to this statement concerning modifications ~~done on~~made to the stilling well infrastructure in the early recording period, which we will illustrate later.


(a)
Existing
New
Water level (m) wrt H_0
6
5
4
3
2
1
0
Chazallon
German
Brillie
Modern
(b)
Check Sheet
Ledger
Chart
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
(c)
Élévation vue de Face.
(d)
(e)

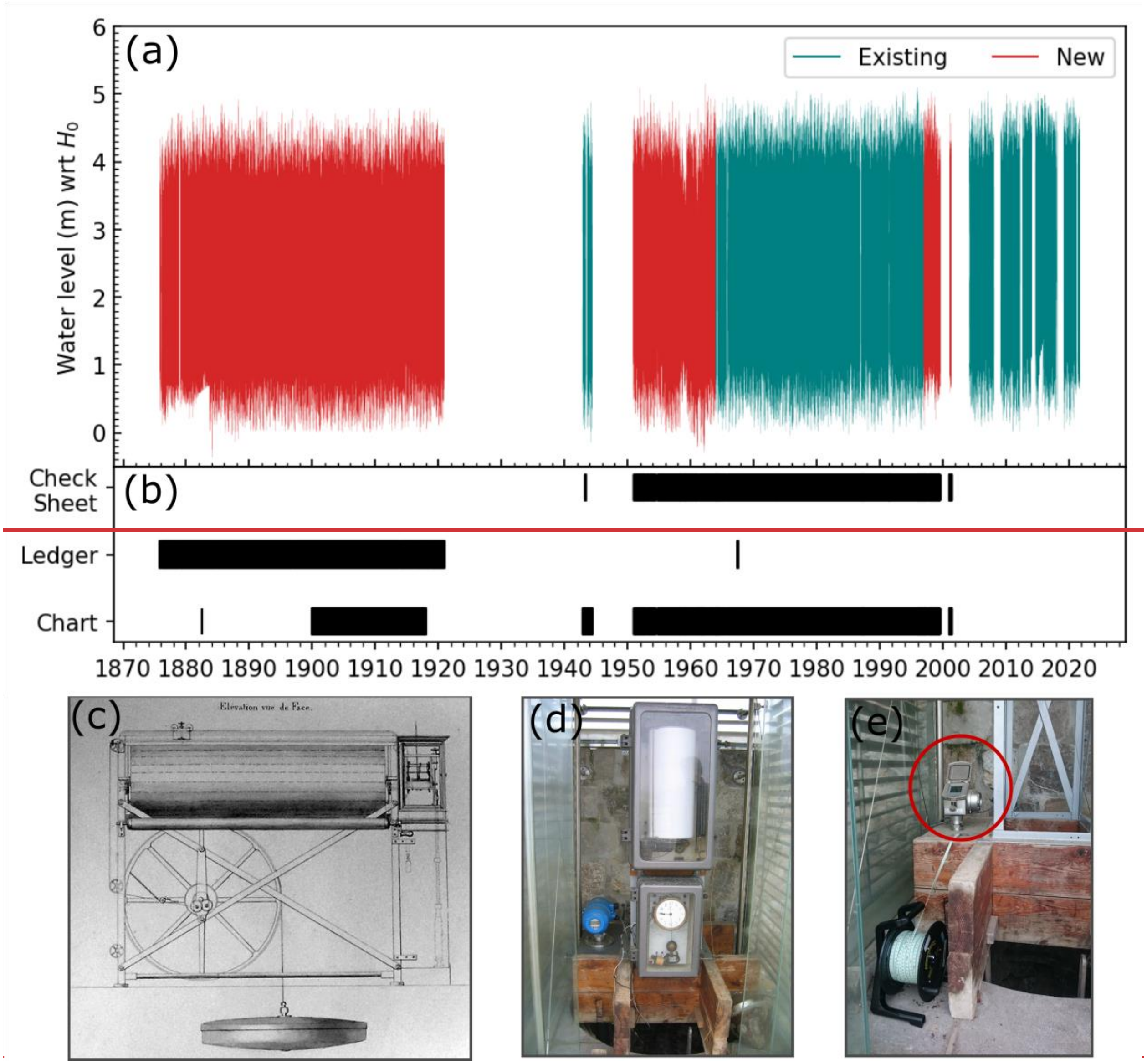


Figure 2~~2~~: (a) Time series of water level at Socoa with digitized data (in red the new datasets from this study). (b) Coverage of the rescued Registries ~~(MR)~~, Charts ~~(MM)~~, and associated check sheets ~~(FC)~~. (c) A schematic of the Chazallon tide gauge (adopted from Pouvreau et al. 2008).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

A chronology of the available ~~water level records~~measurement period, instruments, ~~medium of~~ recording mediums, time system during recording, time sampling before and after digitization and the source archive is summarised in Table 1. The reconstructed time series is in Universal Coordinated Time (UTC), which is further discussed in Section 3.2. As the modern instrument record starting in 2004 is n~~N~~ot ~~being~~ part of the data archaeology exercise, ~~the processing of the~~it ~~modern instrument record starting in 2004~~ is not further discussed in the following sections.

Table 1: Overview of the instrumentation periods, original data storage medium, sampling period of the source and digitized data, and time system of the source observations. ~~**sea level data and their coverage at Socoa**~~

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

AST: Apparent Solar Time.
MST: Mean Solar Time.
UTC: Universal Time Coordinated.
~~SHOM:~~Shom : Service hydrographique et océanographique de la Marine
AD64-Bayonne: Archive Departmental 64 - Pyrénées-Atlantiques ~~-~~– Bayonne~~Béarn Pays basque~~

2.54 ~~Supplemental~~ Complementary metadata

During the ~~archive research~~rescue process~~, other~~ administrative documents were found in the archive ~~, where~~ in which the Socoa tide gauge was mentioned~~, were consulted~~. These documents include tide gauge journals for the Chazallon ~~tide gauge~~ period containing log of tide gauge operations, the correspondence with the ministry (ministry of public works, and ministry of marine and colonies), the engineering and hydrographic survey reports, the quotes for works, drawings etc. The hydrographic survey reports were of particular interest to assess the datum continuity of the tide gauge records (Section 3.3). All t~~T~~he ~~corresponding parts of the~~ documents ~~mentioning the Socoa tide gauge were also transcribed, which~~ form an ancillary part of the available metadata and are provided as supplementary files to the dataset (see Data availability).~~ 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 levels recorded by the Chazallon tide gauge during the 1875-1920 period exists in ~~is stored through~~ two different mediums: ~~–~~ charts and hand-written ledgers. The large charts ~~are~~ were stored for many decades in the archive. They were in an advanced state of deterioration, which prevented them being scanned and rescued. ~~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, o~~Only the ledgers could be ~~were found to be suitable for scanning and rescuing with the available equipment at hand~~scanned and rescued. The scanned documents are stored as PDF (portable document format) files, ~~weighing~~ each 1-1.2 MB ~~each~~large.

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 interval only~~s~~.

For the Chazallon ~~tide gauge~~ period starting from November 1875 to December 1920, 541 ledgers were recovered corresponding~~amounting~~ to 45 years of sea level records. More than 390,000~~k~~ values ~~of sea level~~ were digitized ~~from the ledgers~~manually, which corresponds to several weeks of full-time work. During digitization, the time data were digitized directly as ~~is~~ ~~on~~ in the ledgers. Sea levels 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 1942-2004 ~~the~~ period ~~starting from 1942 to the early 21st century~~ ~~is~~ was scanned (with a photo-scanner) and rescued.~~from their original paper form, thus can be considered rescued.~~ Most of these charts were accompanied by check sheets. These documents contain relevant information on time and water level at the time of replacing the chart paper. The available check sheets were converted into digital form by a photo camera and later used as metadata for identifying problems, especially related to the slowing down of the clock (See Section 4.2). ~~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.~~

Prior to this study, an hourly record of sea level at Socoa from 1964-1996 existed in digital form and was available from the Shom data portal (https://data.shom.fr). Hence, we applied the water level extraction only on the charts that are outside the range of pre-existing digitized data. From 1950 to 2001, the number of available charts amounts to 777. During the scanning phase, the charts were visually sorted into three categories depending on their conditions (good, mildly or badly damaged from mould, and faded) (Supplementary Figure S2). Among the 777 charts, 18.3% (142 charts) were found to be in good condition (Figure S2). Fifty charts were found to have mild mould (mildly damaged), and 32 charts were found badly covered by mould (badly damaged). The majority of the documents, as many as 553 charts (71.2% of the digitized charts), were found to be of the third category with faded water level curve lines.

To extract the water levels 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.~~

Since the algorithm in NUNIEAU is based on colour separation, the water levels are easier to extract from clean charts. ~~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~~ good condition did 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~~These charts ~~. Typically, the mildly damaged charts are~~ were found to be still processable through the processing chain, except for some badly damaged ones which were fully covered by mould~~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~~. These bad damages essentially translated into a loss of data. Finally, in the third category ~~are the charts~~ where the ~~recorded~~ water level curve ~~lines~~ were ~~found~~ very 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~~to process them 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.~~ We have applied NUNIEAU on these charts 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 would be pointless as the higher-frequency fluctuations would have been mechanically filtered by the stilling well (IOC 1985).

The overall process of digitizing ledgers and charts was time-consuming which is known for this kind of data archaeology exercise (Latapy et al. 2022). This is obvious for manually digitizing the ledgers from scanned document to a spreadsheet table. But for the digitization of charts, which is a software-based extraction, it is less obvious. ~~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.~~ In practice, the processing chain could not be automated due to three main reasons. First and foremost, the faded charts needed additional image processing. Second, multiple days of water level were recorded in a single chart, partially overlapping themselves, which required dedicated masks to separate each day. Finally, t~~T~~he zero of the ~~the water level~~ curves was ~~also~~ needed to be set manually ~~set manually~~ for each chart within the NUNIEAU software~~parameterization.~~ ~~Consequently~~In consequence of these delicate pre-processing steps, ~~despite being software-based,~~ the overall chart digitization process was time-consuming, similar to~~like~~ manual digitization from ledgers, as well as challenging to implement in practice. ~~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 simply as ~~UTCZ~~UTC). Over the recording period of the Socoa tide gauge, Apparent Solar Time (AST), Mean Solar Time (MST) and Legal time ~~several time~~ systems were used as ~~described in Section 2 and~~ listed in Table 1. The following subsections describe the detail of the conversion from each time system to UTC.

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~~F~~ Socoa, the metadata confirm that, f~~rom 1875 to 1893, ~~the transcribed records into~~ the ledger records~~s~~ are in local AST. ~~It was ultimately changed in 1894, and~~Afterwards, until 1920 the ~~transcribed~~ records are in local MST. We have first converted the AST to MST by adding their difference over the year, known as equation of time, E, to AST (Hughes et al. 1989, Müller 1995). Here E is ~~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 behaviour 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~~computed using the formulation ~~the~~ ~~almanac~~ published by Bureau Des Longitudes (2011)~~. The equation of time, E, is expressed as~~:

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

with~~Here~~, t is the time difference to 2000-01-01 00:00:00 (in year, negative for earlier years)~~. M is the mean anomaly,~~, and ~~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 $\frac{2\pi\times2.507}{365.25}$ 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 given by the Bureau Des Longitudes (2011) is fitted for 1900-2100, We have used ~~using~~ the same equation ~~before~~ for the period late 1800, which induces only minor errors (order of seconds)~~, 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~~UTC.

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 detailed 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 throughout the year 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~~UTC.

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~~Wöppelmann et al. 2014). A local set of tide gauge benchmarks are usually ~~grounded~~ established around the tide gauge and interconnected ~~with~~ by means of levelling to ~~represent~~ transfer the ZH to each one. Additionally, the practice in France is to include a tide pole and set its zero-measurement mark to the ZH (~~Woppelmann~~Wöppelmann et al. 2006b), but ~~it~~ this procedure was not adopted for Socoa tide poles. We have found two records of tide poles over the full observation period. For each tide poles, the zero-measurement mark of the poles (ZP) are referenced at different height from the ZH. Thanks to the rescued documents on the levelling measurements during past hydrographic surveys, it was possible to reconstruct the relationship between~~of~~ the ZH~~tide gauge~~ and ~~tide pole zeros~~ZP 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 (Institut National de l'Information Géographique et Forestière, IGN) responsibility (SHOM~~hom~~ 2020).

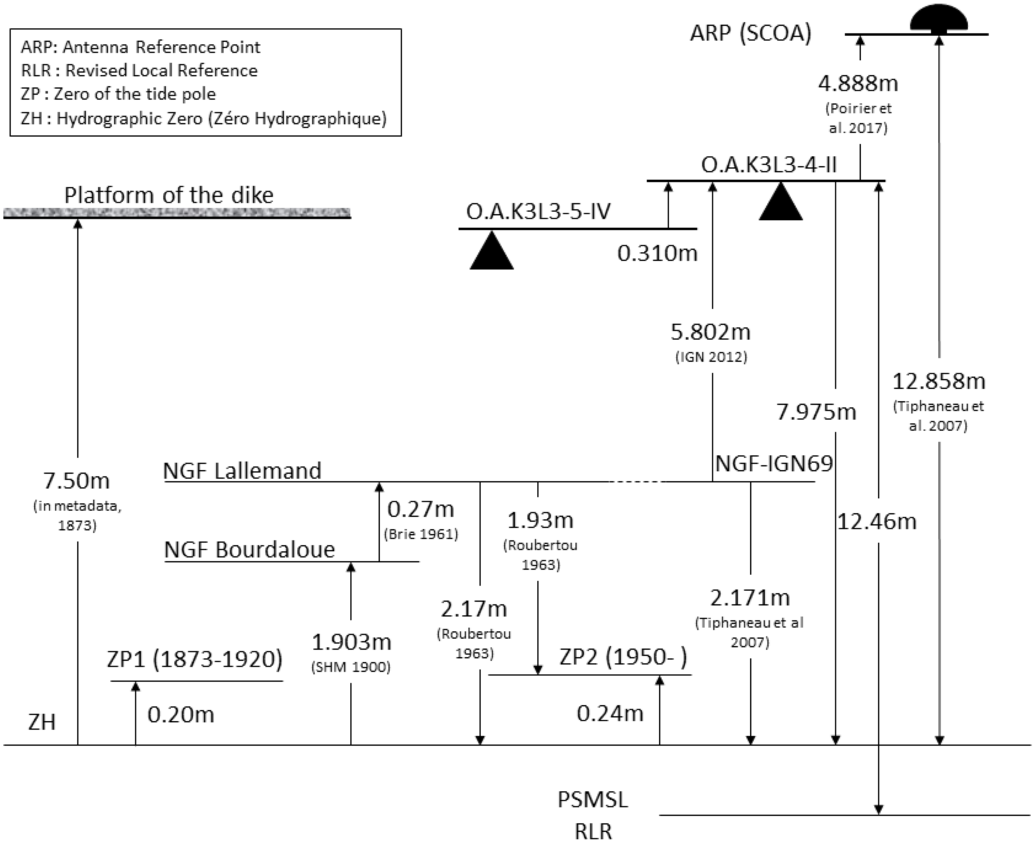


Figure 3~~3~~: Vertical datum definitions and relationships between benchmarks at Socoa tide gauge. O.A.K3L3-4-II is the primary benchmark, O.A.K3L3-5-IV is the benchmark shown in Figure 1e. The references to the measurements ~~is~~ are given inside ~~parenthesis~~ parentheses (in small fonts).

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. This information was reported in regional department archive AD64- Béarn

(Document id: ~~(~~AD64-4S 33) ~~(Pau)~~ and ~~;~~ SHD Vincennes (Document id: ~~–~~DD2-2053). From another published document (Annuaire de marées de 1900, Archive Shom), ZH level was reported to be -1.903m relative to the first national levelling and the 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~~ to the second national levelling datum later established by Charles Lallemand during 1880-1922 (NGF-Lallemand), locating the hydrographic zero at -2.17m ~~from~~ relative to the NGF-Lallemand datum (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 estimated 18 cm above the originally established ~~hydrographic zero~~ZH (Brie 1961). ~~However, it is later noted by a~~A ~~subsequent~~ follow-up investigation~~survey~~ in 1963 ~~that during the survey of 1961,~~ reveals that the tide gauge was suffering heavy siltation and blockage of the connection with the sea during the survey of 1961, causing the deviation (Roubertou 1963). Following the investigation in 1963, the ZH was maintained at -2.17m NGF Lallemand, and the ZP was measured to be 24cm above the ZH. ~~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.~~

All available documents suggest there was no change in the definition of ZH at Socoa. One false alarm was~~In~~ a letter~~to SHOM~~, dated 9 October 1968 addressed to Shom, ~~it is~~where it was mentioned that "the zero of the tide pole" (zero de l'echelle) ~~is~~ was located -2.178m relative to NGF Lallemand datum, and the primary benchmark is located ~~at~~ 5.822m above NGF Lallemand datum. ~~(.~~This ~~is~~ was identified as a mistake based on the survey done in 2007, ~~when~~ which measured 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~~ during 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~~The reported 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). C~~From the available documents, no change in ZH definition is reported.~~urrently, 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).

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). These two steps resulted in a merged time series, which was subsequently assessed to detect any potentially erroneous or suspicious water levels~~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 the rescued metadata, a correction was applied wherever possible, and the corresponding data was flagged.

4.1 Data quality flag

The flag value is ~~built~~ defined as a 4-bit number where 1 means the correction is applied and 0 means 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~~This concept is ~~flag~~ similar to the flag accompanying the ~~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 (corrections_registry.csv) and the charts (corrections_marigram.csv), respectively. These are concatenated into one file for analysis into a file named ‘correction.csv’ ~~These files are~~and henceforth identified as ‘Correction file’ (see Data availability section). In the following section, ~~the~~ different quality control steps~~, and relevant analysis~~ are discussed.

4.2~~1~~ Quality control and corrections

Several basic quality control methods based on visual inspection was applied during the time series construction process. For the ledger~~s~~ data, the digitized tabulated values in spreadsheets were colour-coded, with the colour range between maximum and minimum value to enable visual identification of errors (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~~ obvious height corrections were applied, a tidal harmonic analysis based on validated data was performed, and the recorded water levels were compared with the predicted water levels visually week-by-week (Pugh and Woodworth 2014). 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 (Section 2.5). The tide gauge journal was checked, and corrections were made if necessary~~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~~of 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. This interpolated hourly dataset is the main outcome of this data archaeology exercise and used in the subsequent analysis (See also Data availability). ~~The missing values remained missing.~~

4.3~~2~~ Unresolved data quality issues

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.

4.3~~2~~.1 ~~Slowing-down~~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, i~~In some cases, the ~~beginning~~ start time of the clock was found to be correct with a slow-down at the end. The magnitude of the difference varies from 1 to 10 minutes. Only a small portion of the data (less than 2%) are affected by this problem. Given the ~~time~~ length of the ~~each~~ record in each chart (typically 8-10 days), it is difficult to apply a correction confidently. These values are flagged as values with low confidence (third bit in the flag set to 1).

4.3~~2~~.2 ~~Delayed rising/falling curve~~Possible malfunctioning of the float device

In some instances~~, the position of the floating device seems to have malfunctioned. T~~the ~~associated~~ tidal curves display a quasi- linear rise/fall, instead of the characteristic sinusoidal-like ~~(tidal)~~ evolution (Supplementary Figure S8). This suggests a malfunction of the mechanical system. In all these cases~~ with such a problem~~, the tide gauge regains its normal behaviour in the next tidal cycle. Less than 1% of the recovered data is concerned with this problem. Another issue is linked to siltation (next subsection) which impacted the movement of the float. It concerns about 8% of the total recovered hourly data. The values impacted by this issue are also flagged as ~~potentially bad values~~values with low confidence (third bit in the flag set to 1).

4.3~~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~~ restarting the ~~reoperation~~ operation of the tide gauge in 1950, the stilling well exhibited siltation and blockage related problems (Robertou 1963).

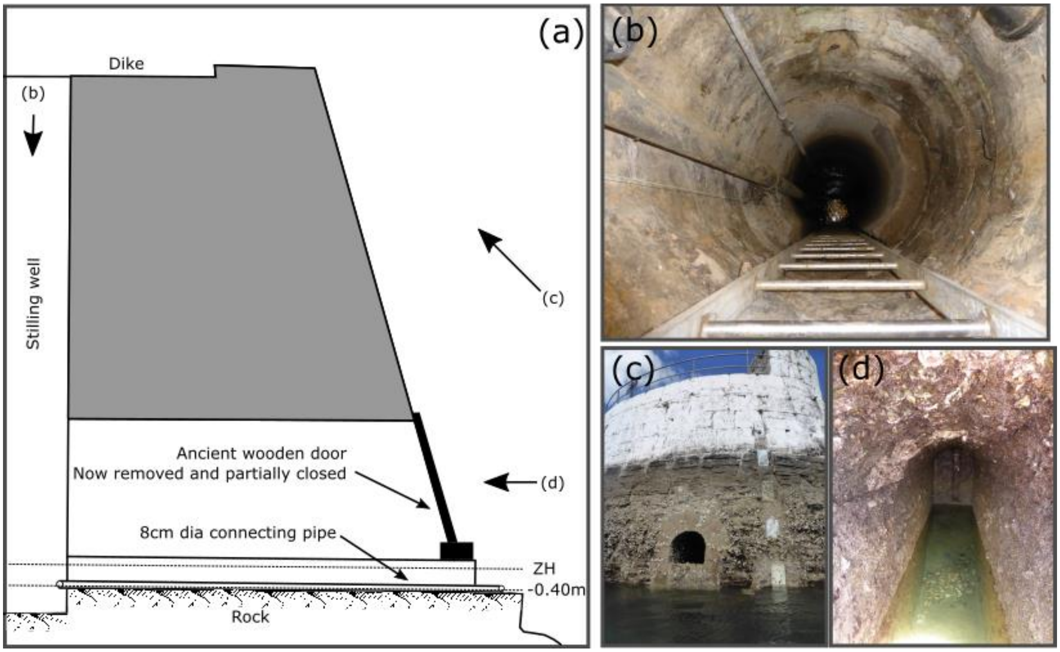
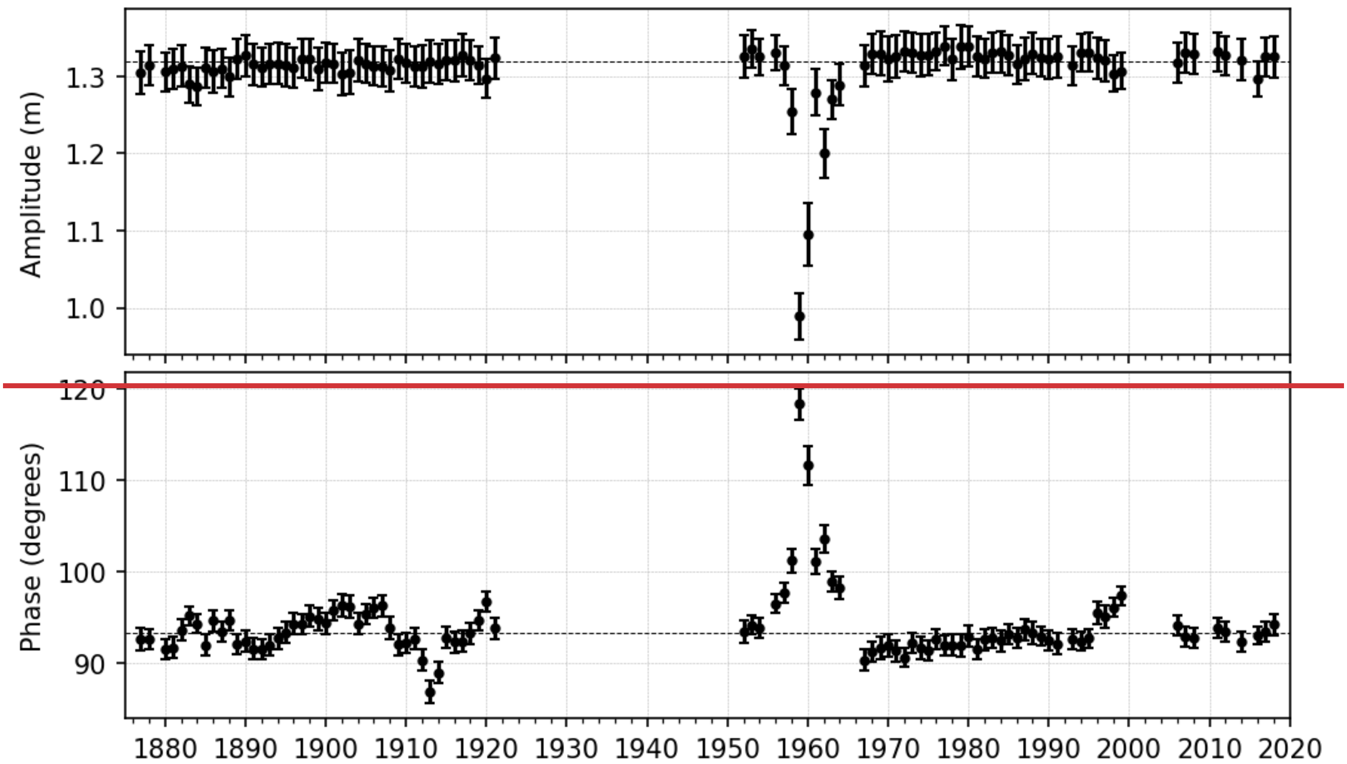


Figure 4~~4~~: (a) Schematic of the current stilling well. (b) View from above inside the stilling well. (c) Entrance to the stilling well (at about 1m above water level). (d) From the entrance, inside the ~~channel~~ passage to the stilling well. Images collected during the fieldwork in 2017 (Poirier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

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 represent~~s~~ the 95% confidence interval.


Amplitude (m)
1.3
1.2
1.1
1.0
Phase (degrees)
120
110
100
90
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

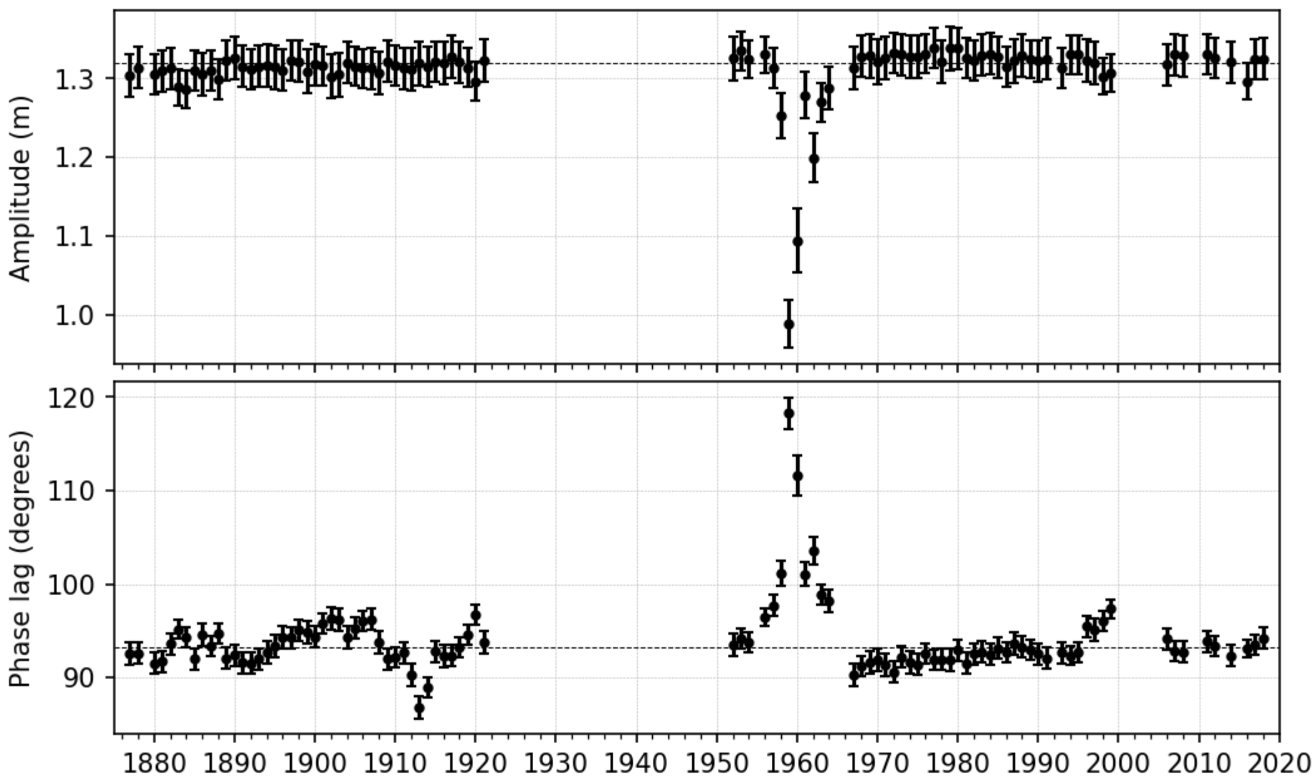


Figure 5~~5~~: M2 amplitude (top) and phase (bottom) calculated for one-year segments using tidal harmonic analysis. The dotted lines correspond to the amplitude and phase computed for the whole time series. Error bars are 95% confidence intervals.

As noted in the literature (~~e.g.~~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 the end of the 1990s (1997~~6~~-2000). Based on the metadata, we apply a siltation flag (fourth bit set to 1) to the data from 1875-11-12 to 1883-08-31. Based on the above-mentioned harmonic analysis we also flag the data from 1955 to 1963, and 1998-1999 period. These amounts to about 29 percent of the total recovered hourly data flagged as impacted by siltation.

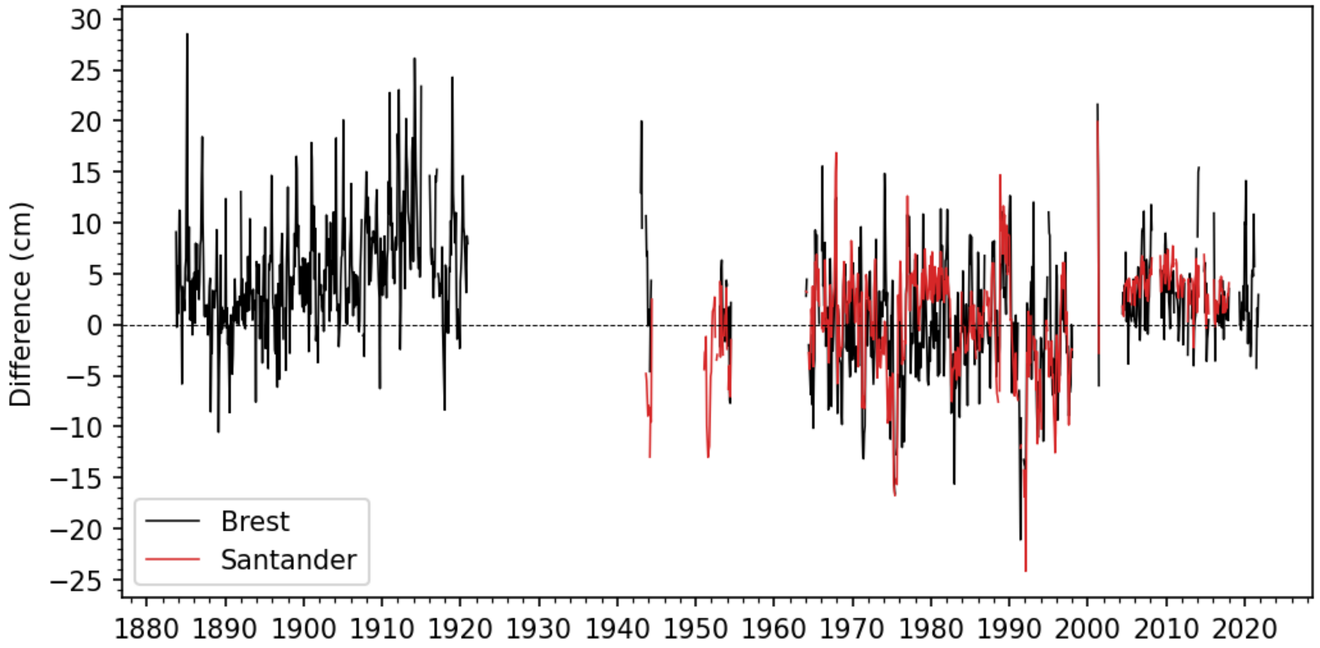
The siltation problem discussed above persists to this date. Currently, the stilling well is cleaned, typically yearly, to maintain an acceptable quality of the data. However, access to the stilling well is challenging, and the cleaning operation is costly. The maintenance is also often perturbed by administrative complications and unforeseen events (e.g., Covid-19 lockdown in 2020-2021). The stilling well, under current condition, also does not conform to the recommended 2m depth of water at Lowest Astronomical Tide (IOC 2016). For Socoa tide gauge, which is currently equipped with a guided wave radar, we recommend a transition from the installation on the stilling well to an installation mounted on the quay of the dike with an unguided open-air radar.

4.4~~3~~ ~~Buddy checking~~Assessment of the vertical datum continuity

One of the commonly used quality control techniques for~~of~~ sea level~~ records~~ is the so-called 'buddy checking', which relies on comparison with mean sea level time series from nearby sites (Pugh and Woodworth, 2014). The difference in monthly mean ~~with nearby~~ sea level with nearby tide gauge~~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, Hogarth et al. 2020). Here, we compare our record with the sea level record from the Brest (obtained from https://data.shom.fr), and Santander (obtained from PSMSL, https://www.psmsl.org/) tide gauges. Brest tide gauge data is one of the well-validated long time series (starting from 17th century) in this region (~~Woppelmann~~Wöppelmann et al. 2006a, 2008) covering the whole time series of Socoa. For Santander, Marcos et al. (2021) extended the Santander time series through data archaeology back to 1875 (see Supplementary Figure S9). However, there are multiple apparent datum shifts in the data during the early years (1875-1910), thus we refrained from discussing the extended time series in the buddy checking for Socoa.

We adopted the PSMSL processing scheme for computing the monthly for Socoa and Brest. First, a Demer~~i~~liac filter is applied on the hourly data to obtain a detided hourly time series 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 levels 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 time series for this analysis.



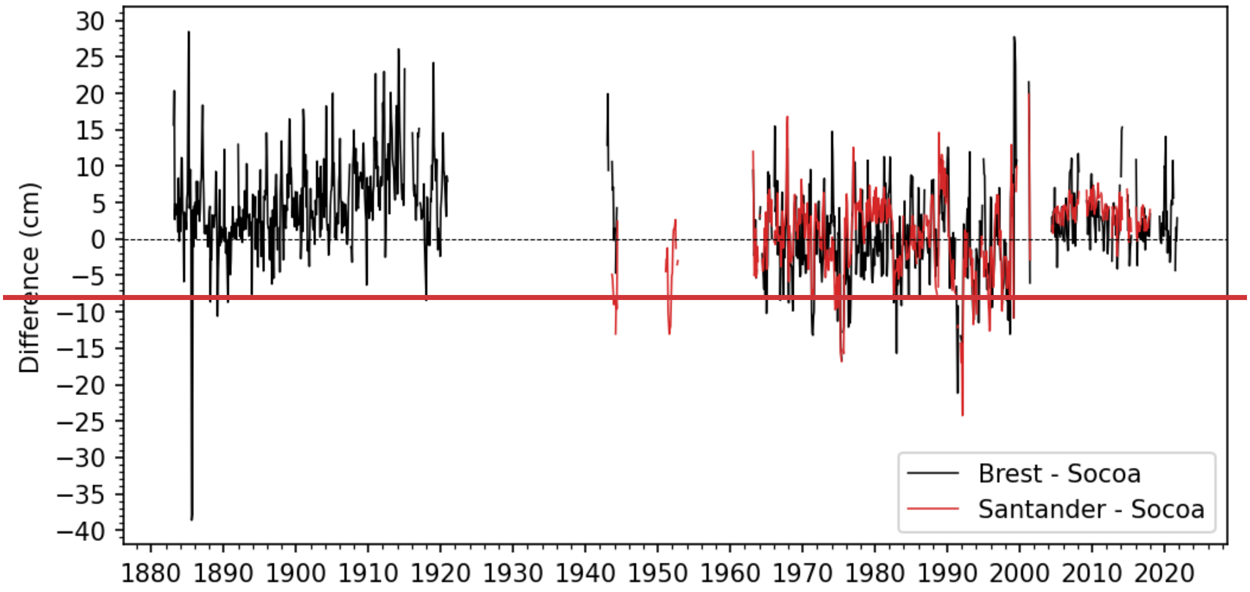


Figure 6~~6~~: Difference in monthly MSL at Brest (black) and Santander (red) relative to Socoa. The mean over 1965-2000 is removed from each station for comparison.~~Buddy checking for Socoa by differencing from Brest (black) and Santander (red) through monthly mean sea level records.~~

From Figure 6, no persistent step-like feature is seen in the Brest minus Socoa time series (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 the literature, this decadal feature is shown to be linked to a large-scale sea-level variability coherent with atmospheric modes of the North Atlantic (Woodworth et al. 2010c, 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 gauges show~~s~~ 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 time series also does not indicate any datum shift, and ~~typically~~ is generally consistent with the Brest minus Socoa time series. However,~~ in the Santander minus Socoa timeseries (red),~~ we see a ~~jump~~ small consistent deviation of 5cm on average 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 datum 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

From the hourly time series for Brest and Socoa, we have computed yearly mean using the yearly PSMSL rules (at least 11 monthly means for a year) and estimated ~~The~~ the trends~~s~~ ~~estimates~~estimate and associated 1-sigma ~~error bars~~uncertainty (~~at Socoa and Brest for selective time periods are shown in~~ Table 2).

Over the same period (1900-2018), for Brest the trend is 1.50~~42+-~~±0.09~~7~~ mm/year, for Socoa ~~1.92~~2.12±~~+-~~0.11~~08~~ mm/year. The benefit of a long time series is clear here – the longer the time series, ~~tighter the error bar~~the smaller the uncertainty. To compare with previously published result by Marcos et al. (2021), we also computed the trend for the non-detided time series shown in Supplementary Figure S9, listed in Table 2 under common period with an 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 computed from yearly mean time series.

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

* Available period for Brest is 1846-2021, for Socoa is 1875-2021

**Computed from annual mean sea level without using a tide-killer ~~filtering the tide.~~filter (Demerliac)

In the last two rows of Table 2, the estimated trend computed over two periods separated by 40 years - Chazallon era (1876-1920) and Brillie era (1963-1997) – is shown. The sea level trend at Socoa during Brillie era (1.95±0.61 mm/year) is noticeably increased (i.e., acceleration) compared to Chazallon era (0.82±0.37 mm/year). Similar magnitude of trend is found at Brest too. During Chazallon era, the trend at Brest is higher compared to Socoa, which is opposite during the Brillie era. Analysis of the factors that contributes to this observed change in trend is out of the scope of this data paper. However, this leads us to another benefit of a long time series, which allows investigating the non-linear evolution of mean sea levels and associated trends. This benefit is illustrated below through the analysis of inflexion points in the trend at Socoa and Brest. 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). To find the inflexion point of the trend, we have analysed the same yearly time series at Socoa and Brest as above. A linear trend analysis is applied over a running window of 20 years. Windows containing two or more consecutive missing values were removed from the analysis. The trend (mm/year) and 1-sigma uncertainty range are shown in Figure 7. We reproduce an inflexion point at around 1887 in Brest, and an estimated inflexion point between 1895-1900 in Socoa.

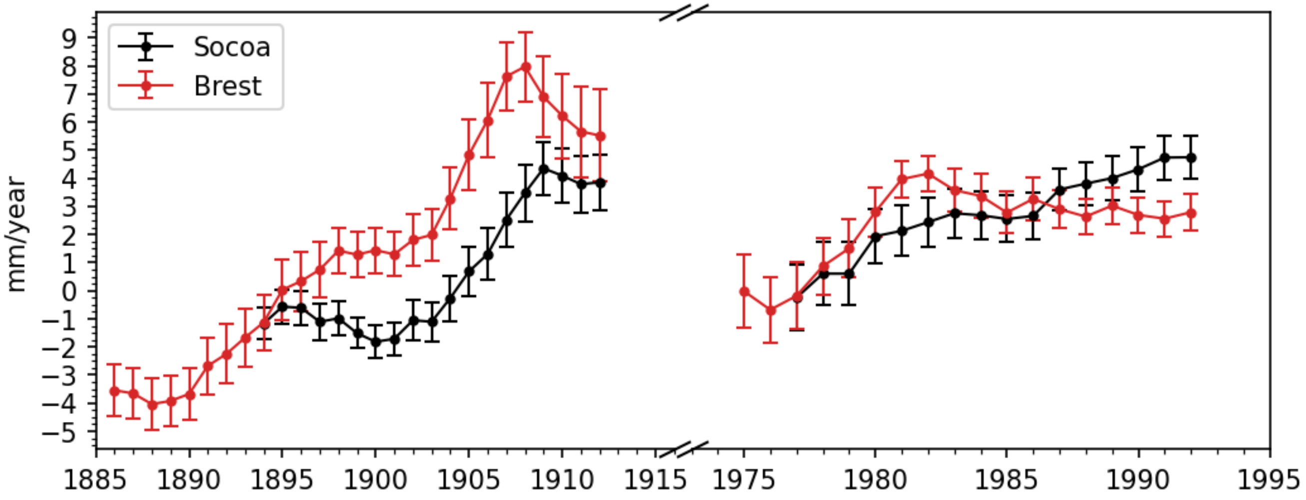


Figure 7: Running trend estimates (20-year windows) for Socoa (black) and Brest (red) during 1875 – 2000. The error bars show the 1-sigma uncertainty range of the trend estimate. Break lines indicates the skipped period when not enough continuous data is available for the analysis.

Multiple drivers may contribute to this inflexion point – decadal variability, long-term climate variability, and climate change induced sea level acceleration. The decadal sea level variability during early 20th century, which is potentially the main contributing factor for inflexion point in trend, is found to be linked with the atmospheric modes of the North Atlantic (Calafat et al. 2012). Jevrejeva et al. (2008) shows that there is a prominent 60-year climatic variation in the trend (acceleration-deceleration), and during the analysis period (1875-1929), the global pattern is a deceleration until around 1910. However, the North-east Atlantic shows a strong deviation from the global pattern with an earlier reversal to acceleration around 1900 (Jevrejeva et al. 2008, Figure 3). Finally, the exact timing of the start of global acceleration of trend due to sea level rise is not accurately answered yet, but studies point towards sometime in the early 19th century (Church et al. 2006, Jevrejeva et al. 2008). Hence, the global trend in sea level rise may have further contributed to the timing of the inflexion point.

6 Data availability

The raw digitized water level ~~timeseries dataset derived from the data digitization~~, the processed dataset,~~,~~ ~~associated~~ metadata, and the python notebooks used for processing ~~the data is~~ are available openly at https://doi.org/10.5281/zenodo.7438469 (Khan et al. 2022). The data repository is organized into 4 sub-directories –

1. `data/` : contains the raw and processed dataset for Socoa (`data/socoa`), and other auxiliary dataset (`data/auxiliary`) used in the analysis.
2. `documents/` : contains inventory of the ledgers and charts (`documents/inventory.xlsx`), transcripts of metadata extracted from the regional archives (`documents/archive_records`), and selected transcripts from the tide gauge journal during Chazallon era (`documents/tidegauge_journal`).
3. `figures/` : contains the generated figures used in the manuscript.
4. `notebooks/` : contains the Python notebooks used to process and analyse the data.

The final hourly time series of water level in meters, vertically referenced to local hydrographic zero (ZH), with data quality flags discussed in this paper is distributed as a comma-separated file `data/socoa/socoa_L4.csv` with metadata in the header. The dataset starts from 1st November, 1875 and stops at 4th October, 2021 containing 101 years with data.

In `/documents`, the transcriptions of the relevant part of the tide gauge journals have been provided with the data as yearly documents. 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), Archives des Pyrénées-Atlantiques - Béarn (AD64- Béarn) and Archives des Pyrénées-Atlantiques - Bayonne (AD64-Bayonne), and SHOM archive are also provided as supplementary files to the dataset.

This dataset is reproducible by applying time and height corrections on the raw uncorrected water level records for Socoa (`data/socoa/socoa_raw.txt`), using the data processing script (`notebooks/01_data_processing.ipynb`) and corrections (`data/socoa/corrections.csv`). Further detail of the files available in the data repository can be found in the include `README.md`- ~~A~~text file.

A~~n~~ continuously updated time series of the Socoa sea level can be obtained from the Shom portal (http://dx.doi.org/10.17183/REFMAR#95).

7 Conclusions

We have done ~~Through~~ a thorough archival research, data-rescue, digitization, and metadata analysis and~~, we have~~ increased the coverage of the existing hourly sea level record at Socoa, Saint-Jean-de-Luz (France) back to 1875. Among the total 702 station-months additional data, ~~by about 40 years~~693 station-months are with more than 50% data per month. This extension of data amounts to about 58 years' worth of new data.

Data quality flags are assigned to the recovered and distributed final hourly dataset from careful inspection of metadata and dedicated analysis of the dataset. The amount of data where time and height corrections were needed and applied with confidence are small (less than 2% in total). Additional flags were assigned to indicate if time or height corrections were applicable but could not be applied confidently due to insufficient information. A very small proportion of data (<1%) is affected by this issue, without considering siltation related problems.

The largest proportions of the flagged data were related to siltation in the stilling well. A dedicated analysis of the data and metadata was done to identify and document periods with siltation. We have identified three main periods, from 1875 to 1893, 1951-1963, and 1998-1999. A dedicated flag was assigned to these periods, which affects 29% of the recovered hourly data. ~~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.~~ Considering the gravity and the recurrent nature of the siltation problem in the stilling well, we recommend a transition from the stilling well to an open-air installation for this tide gauge. This transition should be supplemented with a study of the filtering characteristics of the stilling well to track any impact of the installation change on future sea level measurements.

This extended dataset will be communicated and deposited in international sea level databanks (e.g., PSMSL) 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 same (buildings and stilling well) since its installation in 1875. 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 high temporal sampling of the extended time series.

Besides the final hourly sea level dataset from 1875 to 2021, we also provide the raw data, associated corrections that are synthesized above, computational environment, and notebook as companion datasets (See Section 6). The objective of this is to promote reproducible research and to increase transparency by allowing validation of our computations.

In this data paper, we have not only extended the sea level time series at Socoa, but also showed that 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. During the current data archaeology work, we have also found unrecoverable deterioration of historical paper documents, which underlines the urgency of rescuing these invaluable records. Relevant metadata are also in the same danger of being deteriorated beyond rescue.

Finally, there is a vast amount of untapped tide data and associated metadata worldwide (Pouvreau 2008, Bradshaw et al. 2015, Talke and Jay 2017). Talke and Jay (2017) reported identification of more than 6,500 station-years of previously lost or forgotten tide data over United States. Over 60,000 identified documents have been inventoried in France (See Shom inventory, http://refmar.shom.fr/dataRescue), with 70% already rescued (e.g., scanned), but many remains undigitized (Latapy et al., 2022). Given the time critical risk of losing these valuable scientific and historic information, it is crucial to urgently rescue these datasets, digitize them, and make them available for the scientific community. ~~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 the 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). Last, but not least, we would like to thank the reviewers for their comments and suggestions that significantly improved the manuscript.

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