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Brest sea level record: a time series construction back to the early eighteenth century

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Abstract The completeness and the accuracy of the Brest sea level time series dating from 1807 make it suitable for long-term sea level trend studies. New data sets were recently discovered in the form of handwritten tabulations, including several decades of the eighteenth century. Sea level observations have been made in Brest since 1679. This paper presents the historical data sets which have been assembled so far. These data sets span approximately 300 years and together constitute the longest, near-continuous set of sea level information in France. However, an important question arises: Can we relate the past and the present-day records? We partially provide an answer to this question by analysing the documents of several historical libraries with the tidal data using a 'data archaeology' approach advocated by Woodworth (*Geophys Res Lett* 26: 1589–1592, 1999b). A second question arises concerning the accuracy of such records. Careful editing was undertaken by examining the residuals between tidal predictions and observations. It proved useful to remove the worst effects of timing errors, in particular the sundial correction to be applied prior to August 1, 1714. A refined correction based on sundial literature [Savoie, *La gnomique*, Editions Les Belles Lettres, Paris, 2001] is proposed, which eliminates the systematic offsets seen in the discrepancies in timing of the sea level measurements. The tidal analysis has also shown that shallow-water tidal harmonics at Brest causes a systematic difference of 0.023 m between mean sea level (MSL) and mean tide level (MTL). Thus, MTL should not be mixed with the time series of MSL because of this systematic offset. The study of the trends in MTL and MSL however indicates that MTL can be used as a proxy for MSL. Three linear trend periods are distinguished in the Brest MTL time series over the period 1807–2004. Our results support the recent findings of Holgate and Woodworth (*Geophys Res Lett*) of an enhanced coastal sea level rise during the last decade compared to the global estimations of about 1.8 mm/year over longer periods (Douglas, *J Geophys Res* 96:6981–6992, 1991). The onset of the relatively large global sea level trends observed in the twentieth century is an important question in the science of climate change. Our findings point out to an 'inflexion point' at around 1890, which is remarkably close to that in 1880 found in the Liverpool record by Woodworth (*Geophys Res Lett* 26:1589–1592, 1999b).

Keywords Sea level changes · Tide gauge records · Climate change · Brest

Introduction: short history of sea level observation in France

We owe to the astronomers Jean Picard (1620–1682) and Philippe de la Hire (1640–1718) the first tidal measurements performed at Brest in 1679 (Picard and de la Hire 1680). The exercise lasted for 10 days. It was repeated several years later over a longer period, from June 6 to October 31, 1692 (Cassini 1713). Continuous observations of the sea level proved to be worthwhile for investigations on astronomical parameters of the Sun and the Moon. Henceforth, in 1701, the Académie Royale des Sciences started systematic observations of the tides at the major ports of France with the support of the Navy; their Professeurs d'hydrographie were asked to carry out the observations according to concise rules established by Goüye and de La Hire (1701). Although it started late (1711), the Brest series proved to be valuable to Pierre Simon de Laplace (1749–1827). He assessed his hydrodynamic tidal theory in 1790 by analysing the 1711–1716 data (Laplace

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1790), partially recovered by Joseph Jerôme de Lalande (1732–1807) and published in 1781. Appreciating the need for longer time series to separate the tidal constituents, Laplace instigated the setting up of a new sea level station at Brest, where observations have been performed in various forms with respect to the same datum from 1806 until the present day. The data from the year 1806 were considered of poor quality and were subsequently not preserved (Anon 1843).

For several decades, monthly and annual mean sea level values from Brest have been made available to scientists through the Permanent Service for Mean Sea Level (PSMSL) databank, making it useful for long-term sea level change studies (Woodworth and Player 2003). When high water (HW) levels recorded daily at Brest between 1778 and 1792 were discovered in 2000, we decided to carry out a systematic survey of the numerous historical French archives that may contain sea level observations. This investigation continues but has already proved valuable: A large amount of records have been discovered so far for the eighteenth and nineteenth centuries. In particular, the 1778–1792 Brest data set could be extended backwards to 1756. Long sea level records turn out to be more numerous than the two well-known Brest and Marseille records. This is not very surprising when looking back at history, since France and the United Kingdom were pioneers in sea level observation and recording (Cartwright 1999).

'Archaeological' data are valuable today in the context of climate changes due to global warming. Difficulties like data localisation often arise. The different fragments of information have travelled around the archives during the centuries with a logic that escapes our understanding today. For instance, we found observations of Fort Boyard, Bay of Biscay (1873–1909) in Brest, and the meta-data that explain how they were performed in Rochefort-sur-Mer. This example is not unique. Such activities, data recovery and subsequent data analysis would legitimate "archaeo-mareography" as a new discipline. Important questions must be resolved for these records before any climate study can be undertaken on them. These questions are concerned with the consistency of the past data with those measured by modern gauges: Can they be related to a common datum? What is their quality? Can quantities like mean tide level (MTL) or mean high waters (MHW) be used as proxies for mean sea level (MSL)? The next sections address these important questions for the Brest case study.

Constructing a comprehensive time series

Sea level data sets

Table 1 summarises the various data sets that are presently available for Brest. A data set defines a comprehensive set of observations that are related to the same location and gauge.

The observing sites are within short distance from each other, about 300 m between La Mâture and Bassin de Brest. This latter basin was sometimes referred as Bassin de Troulan or Bassin Tourville in the literature (Levot 1865). It was built by Vauban (1633–1707) between 1683 and 1687. The former sites of Jardins du Roy and Pointe de la Rose designate the same emplacement at the entrance of the harbour, less than 400 m from La Mâture and 700 m from Bassin de Brest. Figure 1 displays a map with the different observing sites.

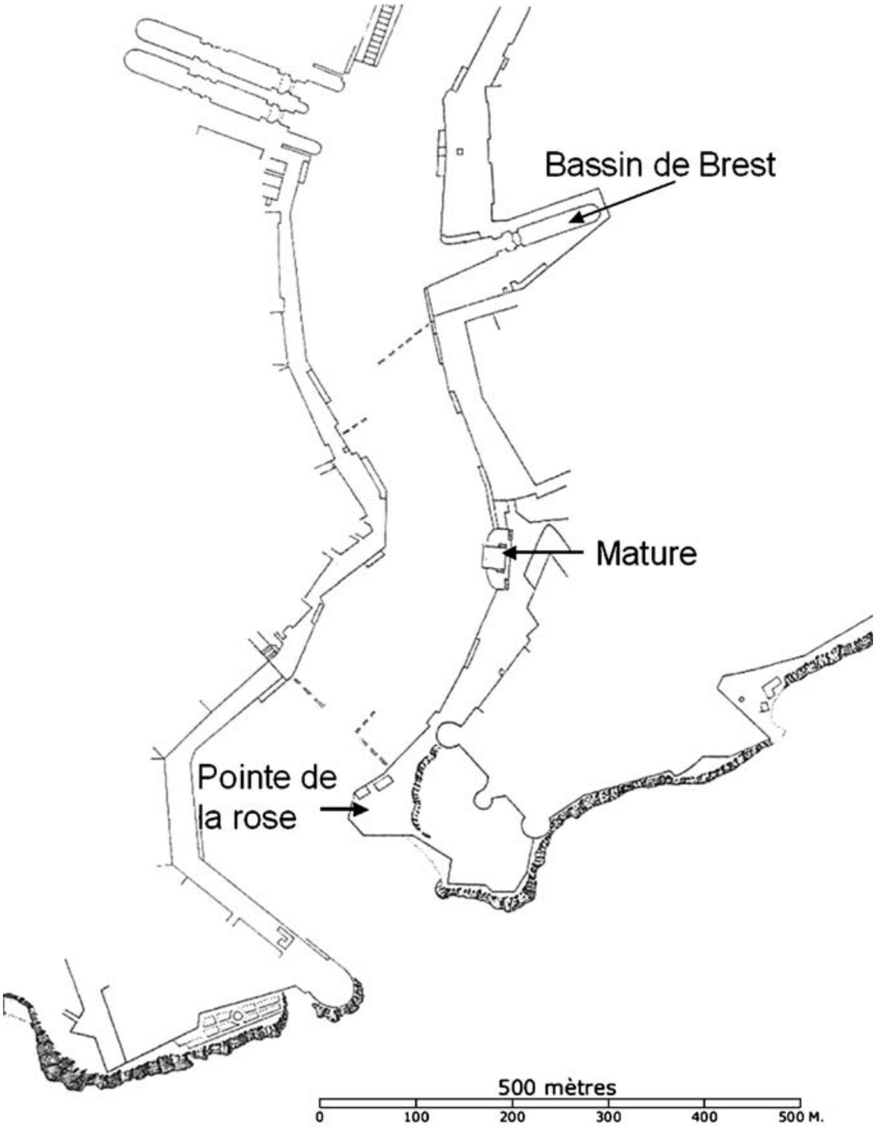
Sea level observations prior to 1842 were made at tide staffs. The observations usually consisted of high and low

Table 1 Overview of sea level data sets at Brest

Set	Period	Location	Gauge	Type	Historical archive
1	1679/09 (8 days)	Jardins du Roy			Acad. des Sciences
2	1692/06–1692/10	Pointe de la Rose	Marker 'Rocher de la Rose'	HLW	Obs. de Paris
3	1711/06–1716/09		Tide staff '1'	HLW	Obs. De Paris
4	1757/08–1778/06	Bassin de Brest	Tide staff '2'	HW	Acad. des Sciences
	1778/01–1792/12				Obs. de Paris
5	1807/01–1811/12	La Mâture	Tide staff 'A'	HLW	EPSHOM
6	1810/01–1810/12	Bassin de Brest	Tide staff '3'	HLW	EPSHOM
	1812/01–1836/04				
	1837/05–1837/09				
	1850/01–1850/12				
	1817/01–1817/12				Service Hist. Rochefort
	1819/06–1832/10				Archives Nationales
7	1846/01–1857/06	La Mâture	Tide gauge 'A'	Hourly	EPSHOM
	1860/05–1944/06				
	1856/01–1856/12			HLW	
8	1953/01–ongoing		Tide gauges	Hourly	EPSHOM

A data set is defined as a comprehensive set of observations with respect to same location and gauge. Two types of observations can be distinguished: (i) high and low waters (HLW), sometimes only high waters (HW), and (ii) hourly data. Note: the observations of the year 1713 were never found (Lalande 1781)

Fig. 1 Map of Brest harbour showing the locations of the different observing sites



water (HLW) levels measured in 'pieds', 'pouces' and sometimes 'lignes'. The relationship to the metric system is given by 1 pied=12 pouces=144 lignes=0.32484 m (hereafter, all feet and inch values refer to these French units). In 1842, Rémy Chazallon (1802–1872) devised an automatic recording sea level gauge for which he was rewarded with a silver medal by the 'Société d'Encouragement' (Chazallon 1859). A first gauge was installed at Toulon in 1842 and at Brest in December 1845. Two main types of observations can therefore be distinguished in Table 1: (i) observations of HLW, sometimes only HW were recorded, and (ii) hourly data. Of particular interest are the newly discovered observations of HW that cover the period 1757–1792, as well as the HLW data of 1810, 1812–1837, 1850 and 1856, last but not the least is the 12 years of tide gauge hourly data covering the 1846–1857 period, tabulated in books from the tide gauge readings. The 1757–1792 record is unique in the fact that no exact time is provided, just the indication of HW. Accurate tidal predictions however may help overcome the lack of time information.

Datum reconstruction

Ever since the first automatic tide gauge was installed in Brest, sea level observations have been performed at the same location, La Mâture (see Table 1). Courtier (1933) points out that the first tide gauge and its associated tide staff were installed by Chazallon in such a way that their zeros were coincident with the zero of the tide staff at Bassin de Brest. This information is confirmed in SHOM (1861). Courtier (1934) further reports that every guarantee on the datum connection was provided. He considers the datum control carried out by Ing. Trotté de la Roche in 1839 at Bassin de Brest and concludes that all observations carried out since 1810 (data sets 6, 7 and 8 in Table 1) are referred to a common datum, the so-called 'Zéro hydrographique' (ZH). This datum is a local datum determined with respect to a set of benchmarks. It was established in 1816 by Charles de Beautemps-Beaupré (1766–1854), who adopted the zero of the tide staff from Bassin de Brest as chart datum (Bajot 1824). SHOM (1933) indicates that the datum of the data set 5 in Table 1 is 4.405 m above the chart datum. The discovery of 1 year of raw HLWs simultaneously performed in 1810 at both sites, Bassin de Brest and La Mâture, allowed us to confirm this value to be 4.415±0.001 m.

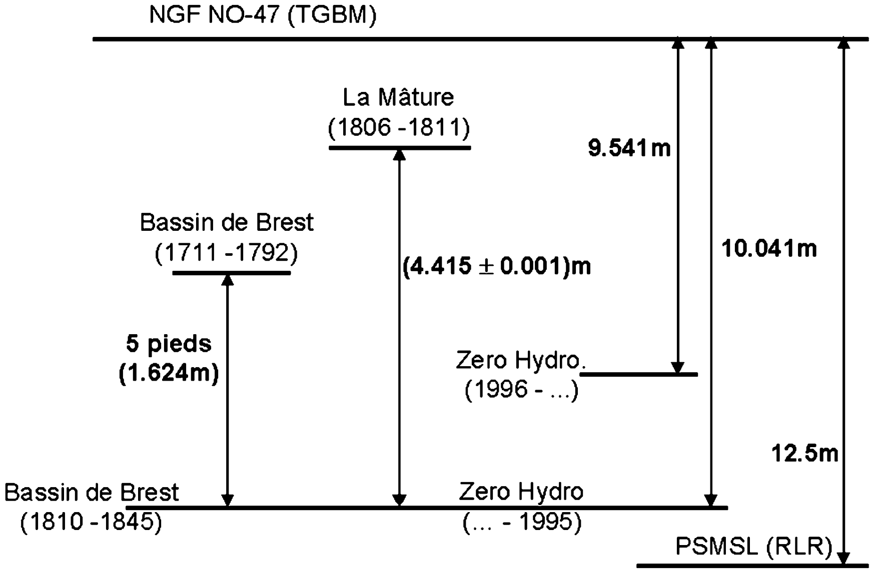
These facts enabled us to construct with confidence a composite sea level record from the combined Mâture and Bassin de Brest data, starting in 1807 and still ongoing; these values are all expressed with reference to the same datum, the ZH. The ZH was changed at Brest in the mid-1990s for local navigation purposes (Simon and Lahaye-Collomb 1997). A constant of 0.5 m was applied to convert the sea level values prior to January 1996 into the new ZH. Figure 2 shows the relationships between the tide staff zero, the tide gauge benchmark (TGBM), and outlines the constants applied to the data from the different records to refer the data to the ZH.

The connection of the eighteenth century records to the composite Brest time series starting in 1807 is very challenging. An extensive investigation of the historical archives has been started on this issue. We present here the main facts that have been assembled so far. The 1756–1778 and 1778–1792 records of set 4 in Table 1, although found at different archives, are definitely referred to the same tide staff zero as Lalande stated in 1781. This was confirmed by the careful examination of the six overlapping months in both records, from January to June, 1778. Historical documentation shows that tide staffs were usually installed in such a way that their zero coincided with the level of the dock sill. This is clearly stated in Thevenard (1778). Lalande (1781) provides an even more detailed description of the tide staff installation at Bassin de Brest. The practical navigational rule of installing the tide staff zero coincident with the level of the dock sill was still in use in the early nineteenth century (Anon 1843). However, the tide staff zero from the 1807 onwards records is clearly not the same as that from the eighteenth century. An explanation can be found in Clairbois and Blondeau (1785): The Bassin de Brest was deepened by 5 ft in 1783. The authors state that the deepening was the only conversion undertaken to the basin. The 1756–1792 time series presents no evidence of discontinuity at around 1783, showing that the tide staff did not undergo any change either. However, the installation of a new tide staff somewhere between 1792 and 1806 followed the above mentioned practical rule and should subsequently be 5 ft below the previous one. Levot (1865) reviews the history of Bassin de Brest. He confirms the digging of Bassin de Brest by 5 ft and reports that no other significant conversion was carried out at Bassin de Brest up to 1864. Considering the existence of Bassin de Brest since 1687, the 'Académie de Marine' building a few metres from there and the practical rules of observation in use, we plotted the 1711–1716 and 1756–1792 HW records together with the 1846 onwards data (the "Tide staff data" section explains how HWs are derived from the hourly values). Figure 3a gives a first idea of the consistency of the HW level time series when applying a 5 ft correction to the eighteenth century records. The annual MTL are displayed alongside the annual MHW for comparison purposes (Fig. 3b). The "MSL vs MTL" section details how the MTL values were obtained.

The moon nodal cycle of 18.61 years clearly appears in the MHW time series (Fig. 3a). Its amplitude is estimated to be 0.065 m with a formal error of 0.004 m. A piecewise linear trend was removed over the period 1711–2004, with breakpoints at 1800 and 1890 before fitting the amplitude and phase of the nodal cycle to the annual MHW values in the least-squares sense. The root mean square (RMS) of the residuals is 0.034 m. The 'bump' around 1915 in the MTL time series, also visible in a MSL plot, has not found any explanation yet. By comparing both curves in Fig. 3, one can observe that this bump might also have been more apparent in the MHW time series if it had not been coincident with a low phase of the nodal cycle.

The question which naturally arises then is: What is the accuracy of the 5 ft adjustment value? Levelling and civil engineering techniques were able to provide results at the millimetre level precision, but did they care to get such a

Fig. 2 Relationship between tide staff zeros, tide gauge benchmark and datums at Brest



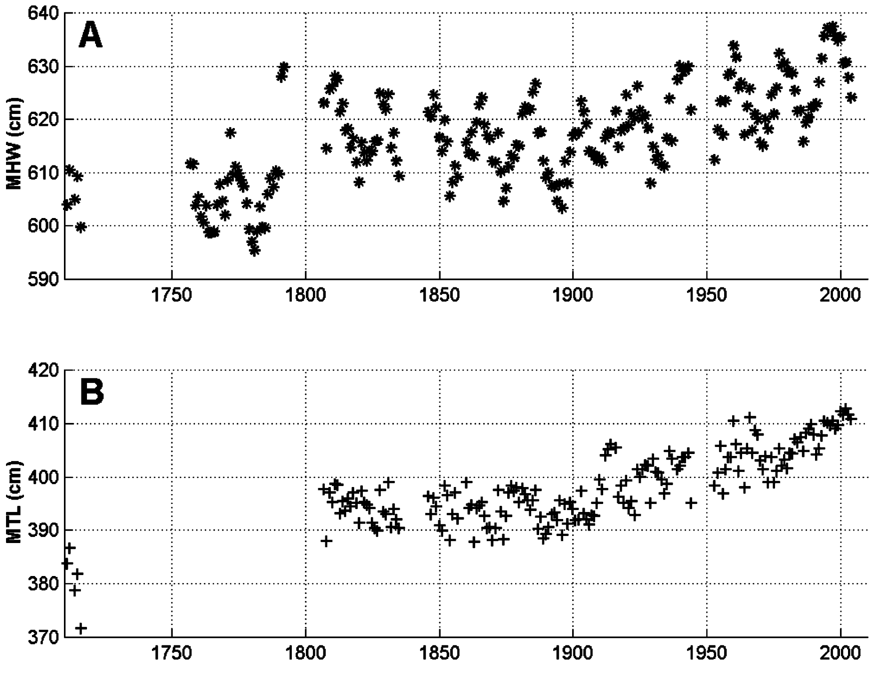


Fig. 3 Annual mean high water levels (**a**) and annual mean tide levels (**b**) for Brest, assuming the relationships given in Fig. 2

precision in the estimation of this value? Millimetre to centimetre level precision were common standards at the time in hydraulic engineering. Still it is remarkable that the correction is exactly 5 ft. Is the reported value the exact number derived from the measurements or a rounded number? In the latter case, the uncertainty of the 5 ft value could be as large as 0.08–0.16 m (quarter to half of a foot). The issue deserves further investigation to reduce the present level of uncertainty. Several historical archives have not been investigated yet, in particular the civil engineering archives at ‘château de Vincennes’ in Paris and at ‘Ponts et Chaussées’ in Marne-la-Vallée. Most of the Bassin de Brest has remained unchanged since its construction according to Monsieur Littoux, historian of the Naval constructions in Brest (DTM), specialising in basins and docks (personal communication). The techniques used to dig the basin did not move any of the stones of the basin walls. Hence, if a plan were to be found with precise quotations of the dimensions or levels of the main structures of Bassin de Brest, we might recognise them and perform a levelling to present-day TGBMs.

Addressing the question of data quality

The main approach used to control the quality of Brest observations is based on the inspection of the residuals that are obtained from the harmonic analysis of the hourly heights of sea level. We used the MAS software for this purpose, a set of programs developed by B. Simon at SHOM which implements a general method for analysing hourly sea level heights. It basically provides tidal predicted values, residuals (predicted minus observed) as well as values for harmonic constituents. The standard list consists of 143 constituents, but it can be extended. Considering the large data span available at Brest, a set of 247 tidal constituents was estimated on the basis of best quality measurements over the 1846–2005 tide gauge period. These are the constituents that were used hereafter to compute the tidal predictions and derive the residuals (with an assumption of no significant change in the ocean tide at Brest in the intervening period). Several quality control iterations were required. Residuals were manually inspected leading to the examination of the records and subsequent corrections where appropriate. Correcting large data sets in such detail is an arduous and time-consuming task, but it proved to be worthwhile. For example, we may mention the several years of data published by PSMSL, which were identified as those corrected for the inverse barometer (1937, 1939–1943). The registers at SHOM had several columns with tabulated values; a misunderstanding led to the barometer-corrected values instead of the true observations being supplied and published.

Sundial correction: 1711–1714

When dealing with long records covering several centuries, attention has to be given to time system definitions: ‘apparent solar time’, ‘mean solar time’… and their application, legal and practical. To reduce the time of sea level observations into the standard time system [universal time (UT)], the following corrections were applied to the Brest 1711–1716 record:

- correction from apparent solar time to mean solar time at Brest by applying the ‘equation of time’ given in Savoie (2001);
- correction from mean solar time to UT by adding 17.98 min, a value corresponding to the difference in longitude between Brest and Greenwich

An additional correction is required to the observations prior to August 1,1714. On August 1, 1714, M. Coubard discovered and corrected an error in the alignment of the sundial. Cassini (1720) reports that the correction to apply is −17 min. However, an analysis of the residuals between predicted and observed times of HLWs for 1711–1716 suggests that the correction should not be a mere constant (Fig. 4a).

The literature on sundials confirms this result (see, for instance, Savoie 2001). It is a function of the Sun's position and the misalignment angle (*d*) of the sundial's style towards the North celestial pole, which can be computed from (Savoie 2001)

$$T = H - F = d \cdot (\cos\phi \cdot \tan\delta \cdot \cos H - \sin\phi)$$

where the various quantities are explained in Fig. 5.

Assuming M. Coubard checked the sundial at noon July 31, 1714, as it was usually performed in the Navy (Beautemps-Beaupré 1829), we obtain a misalignment angle (*d*) of 7.69° corresponding to the −17 min error in time at noon. Figure 4b shows that the subsequent time correction reduces the time residuals oscillation in Fig. 4a, but a bias can be seen, as well as a remaining slight oscillation. After several tests, we found that if the misalignment angle (*d*) was 5.87°, corresponding to a time error of −13 min instead of −17 min, the bias disappears (Fig. 4c). It is interesting to note in Fig. 6 that this latter correction has an average value of −17 min, which corresponds to the value mentioned by Cassini (1720), although he did not specify that it was meant as an average correction.

Figure 4c shows a dispersion of about 6.5 min (standard deviation) in the residuals between predicted and observed times of HLWs. This dispersion is consistent with what might be expected for a tidally dominated location, where the presence of surges can alter the levels of HLWs but not affect their times to any great extent.

Tide gauge data

The errors associated with the tide gauges are complicated to assess. One way of doing this is by looking at the non-tidal component of the observed sea level values, that is the residual between predicted and observed heights of sea level. Figure 7 shows annual RMS of hourly differences between predicted and observed water levels after removal of daily mean differences, which amounts to filtering out the fluctuations with a period longer than a day. The original purpose of this procedure was to evaluate the consistency between observations and predictions, but it also proved to be very helpful for detecting observation defects. The figure shows a constant value of about 0.05 m until the year 1945, when the tide gauge was destroyed during Brest bombing at the end of World War II. After reconstruction in the 1950s, the quality of the observations deteriorated, this can be seen in the RMS increase. Better figures were obtained after 1990 when a modern digital tide gauge was installed.

The comparison with the adjacent sea level record of Newlyn, UK, provides an external means to evaluate the quality of the Brest tide gauge data. Newlyn is located about 200 km from Brest. Its MSL values were obtained from the 'Revised Local Reference' data set of the PSMSL. The signal structure is very similar in both records: the zero-lag correlation coefficient of the detrended monthly MSL time

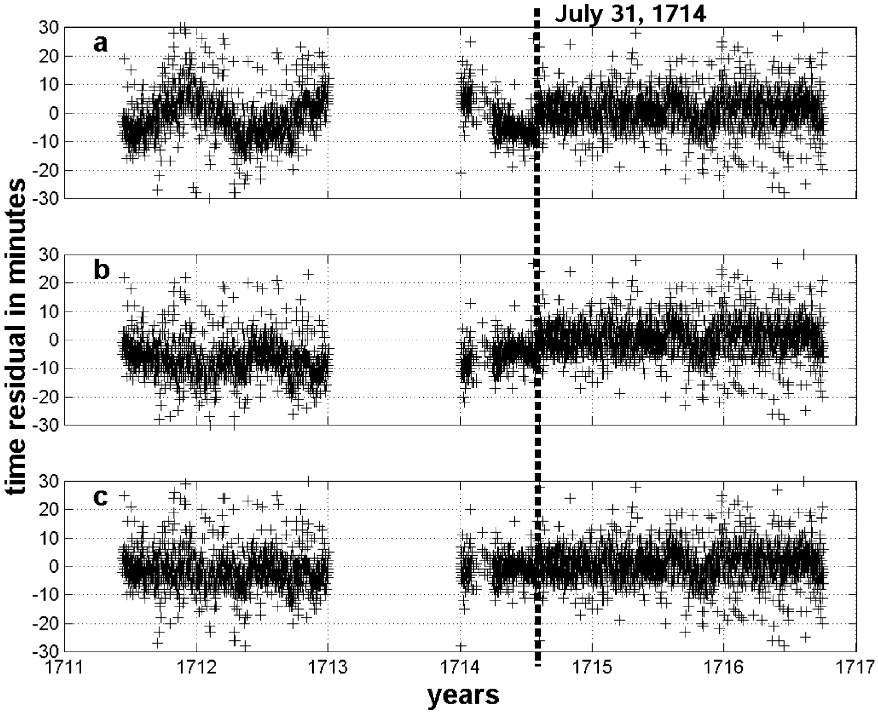
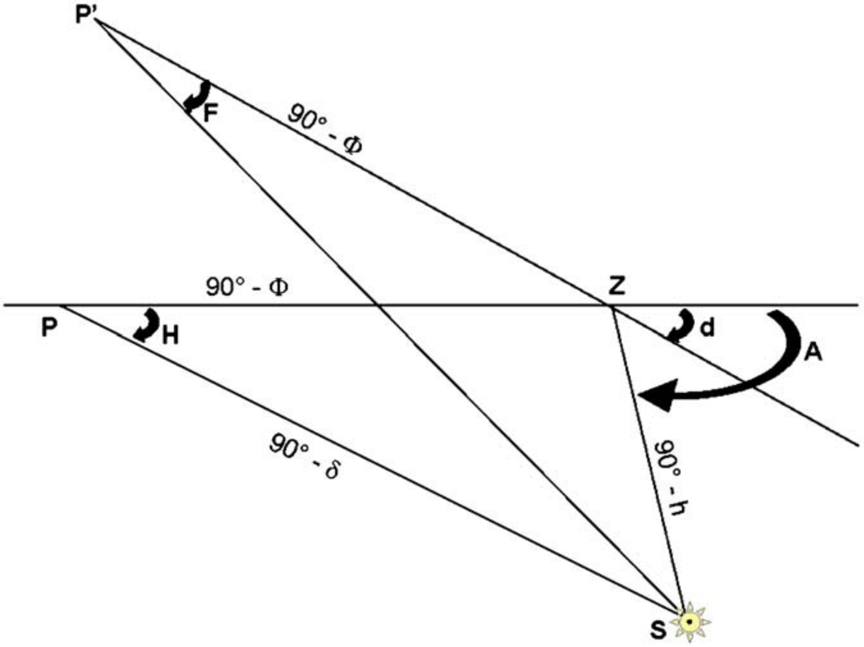


Fig. 4 Residuals between observed and predicted times of the 1711–1716 high and low water levels record when various corrections are considered. **a** A constant correction of −17 min. **b** A correction function of the Sun's position with a misalignment angle corresponding to −17 min on August 8, 1714. **c** Same correction as **b** with an adjusted angle to minimise the residuals

Fig. 5 Geometry of the problem of a misaligned sundial's style, from Savoie (2001). *Z* zenith, *S* Sun, *P* true pole, *P'* sundial's pole (style), ϕ latitude of the site, δ Sun's declination, *A* Sun's azimuth, *h* Sun's height, *F* erroneous time angle, *H* true time angle, *d* gnomic orientation error

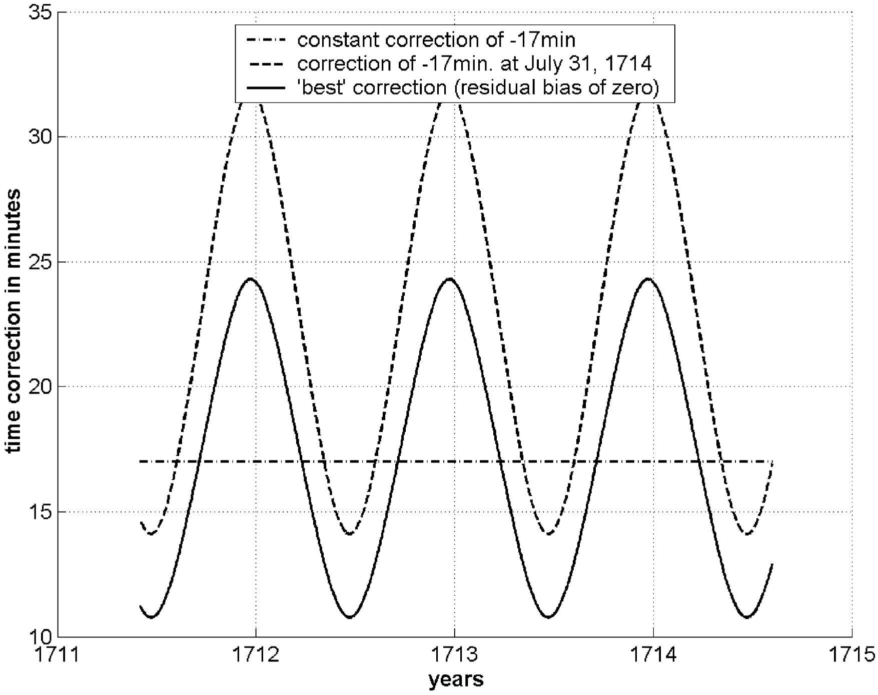


series over the common period of 1916–2003 is 0.90, significant at the 99% confidence level, reflecting a coherent sea level variability mainly due to seasonal steric and meteorological effects. The RMS of the detrended annual MSL differences is 0.02 m. This value is within the range of 0.01 to 0.03 m as reported by Woodworth (2003) for 'high-quality' records. The trends are 1.75±0.11 mm/year for Newlyn and 1.31±0.13 mm/year for Brest over the common period 1916–2003. The values are consistent with the literature (see, for instance, Douglas 1991; Araujo et al. 2002). The differential trend of 0.43 mm/year may come from different vertical movements of the land where the tide gauges are settled. According to Peltier (2001), the difference cannot be attributed to postglacial rebound. The magnitude of this effect is almost identical at both sites: 0.25 vs 0.26 mm/year.

Tide staff data

Figure 8 shows similar statistics as Fig. 7 for the HLW levels. To get a relative idea of the data quality with respect to the

Fig. 6 Summary of the various time corrections that have been tested



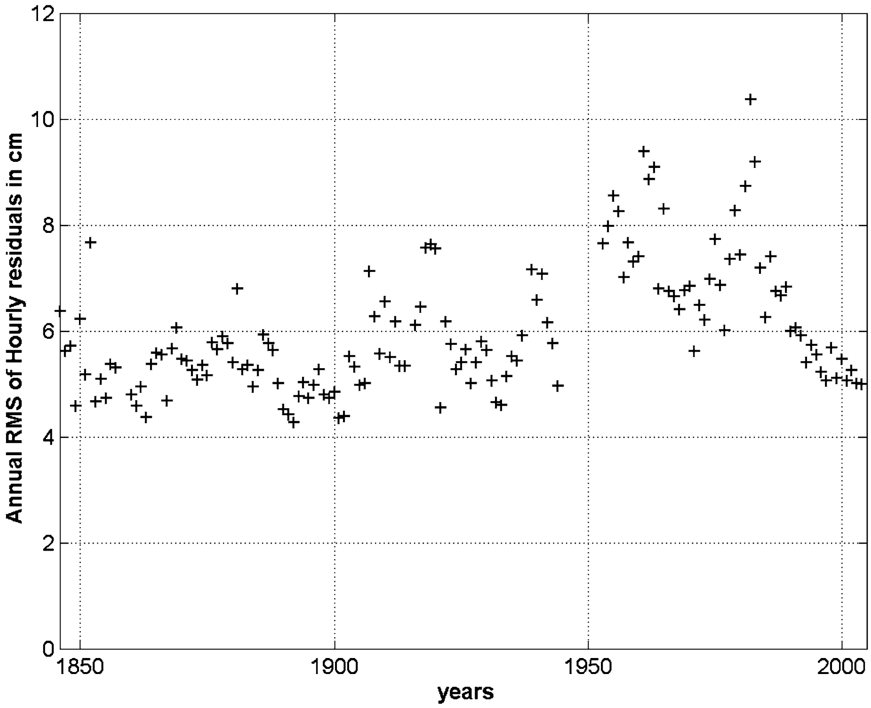


Fig. 7 Annual RMS values of residuals between predicted and observed hourly values of sea level after removal of daily mean differences

tide gauge era, HLW levels were computed from the hourly heights using a cubic spline interpolation procedure. The cubic spline functions are fitted to four consecutive hourly heights around the extreme values. The discovery of both HLW observations and hourly tide gauge tabulated values for the year 1856 allowed us to test the ability of the cubic spline procedure to accurately interpolate the HLW levels. The results show that HWs are underestimated systematically by about 4 mm, while low waters are overestimated by 3 mm. This sums up to a systematic underestimation of the mean tidal range of 7 mm, which is a value slightly larger than the 4 mm found by Woodworth et al. (1991) for Liverpool. Figure 8 confirms an annual RMS of about 0.05 m for the tide gauge observations, while the tide staff observations show a larger RMS of about 0.06–0.08 m, sometimes more. Such larger RMS values are consistent with the difficulty of precisely reading the tide staff in a moving water level. The tide gauge stilling well reduces this problem.

Tide staffs were usually graduated in inches prior to the introduction of the metric system in the 1790s. This was the

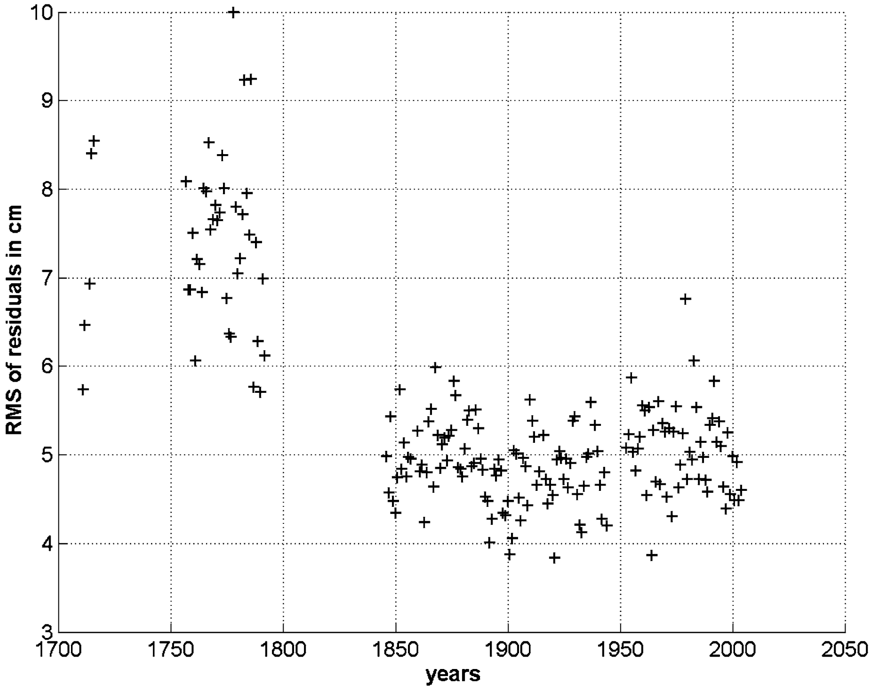


Fig. 8 Annual RMS values of residuals between predicted and observed high and low water values of sea level after removal of daily mean differences

case for the tide staffs at Brest even up to 1835 (Anon 1843). The distribution of inch values for the foot–inch measurements in the 1757–1792 record (Fig. 9) gives an idea of the rounding of the heights and the subsequent uncertainties related to these measurements (Woodworth 1999a). If HLWs were recorded to the nearest inch, every value from 0 to 11 would a priori be represented approximately an equal number of times in the distribution, about 2000 times in average (Fig. 9). Two values however exceed by far the average, 0 and 6. Figure 9 shows that these exceeding values are mostly compensated by two deficit values either side of them: 11 and 1 either side of 0, and 5 and 7 either side of 6. An uncertainty of the order of 1–2 in. in measurements from the sole rounding effect can therefore be inferred. The two intermediate values, 0 and 6, might have been preferred in the presence of high sea states, in which case the associated uncertainty must have been larger. But as Pugh (1987) and Woodworth (1999a) point out, the statistical errors would reduce to millimetre accuracy in monthly or annual averages, although each individual observation was measured with an uncertainty of several centimetres, as long as few data records are missing in the series, and there are no systematic errors in the readings.

MSL vs MTL

Influence of non-linear tidal waves

MTL is defined as the average of the HLW levels in a specified period (see, for instance, Pugh 1987). MTL is not the same as MSL, because the tidal curve is not necessarily symmetrical with respect to the mean level. The difference depends on the form of the curve, which is influenced by shallow-water tidal harmonics. The systematic difference may be computed from following equation derived from the theory of tidal harmonic analysis (see, for instance, Pugh 1987 or Simon 2005):

$$MSL - MTL = A_{M_4}\cos(2\cdot g_{M_2} - g_{M_4}) + A_{M_8}\cos(4\cdot g_{M_2} - g_{M_8}) + \ldots$$

where, A_{M_4} and A_{M_8} are the amplitudes of the tidal constituents M_4 and M_8, respectively, and g_{M_2}, g_{M_4} and g_{M_8} are the phase lags at Greenwich of M_2, M_4 and M_8 tidal constituents.

According to the tidal analysis performed over the 1846–2005 tide gauge series, in which 247 harmonic constituents were estimated, we found a systematic difference of 0.023 m at Brest. Bouquet de la Grye (1890) reports a difference of 0.029 m, but he did not explain how he got the said value. In conclusion, MTL and MSL values should not be used together in a single time series at Brest without taking into account this systematic effect.

Significance of MSL and MTL trends

A simple test has been carried out to investigate whether MTL can be used as a proxy for MSL. Annual values of MSL and MTL were computed from the 1846–2005 tide gauge series of hourly values. HLW levels were previously computed from the interpolation procedure described in "Tidal staff data" section. It was decided that an annual mean requires data from at least 300 days of valid data in the year to be computed, a criterion which seems acceptable to avoid significant biases in the trends from the seasonal cycle over more than a century time period (Araujo et al. 2002). The trends in MSL and MTL were

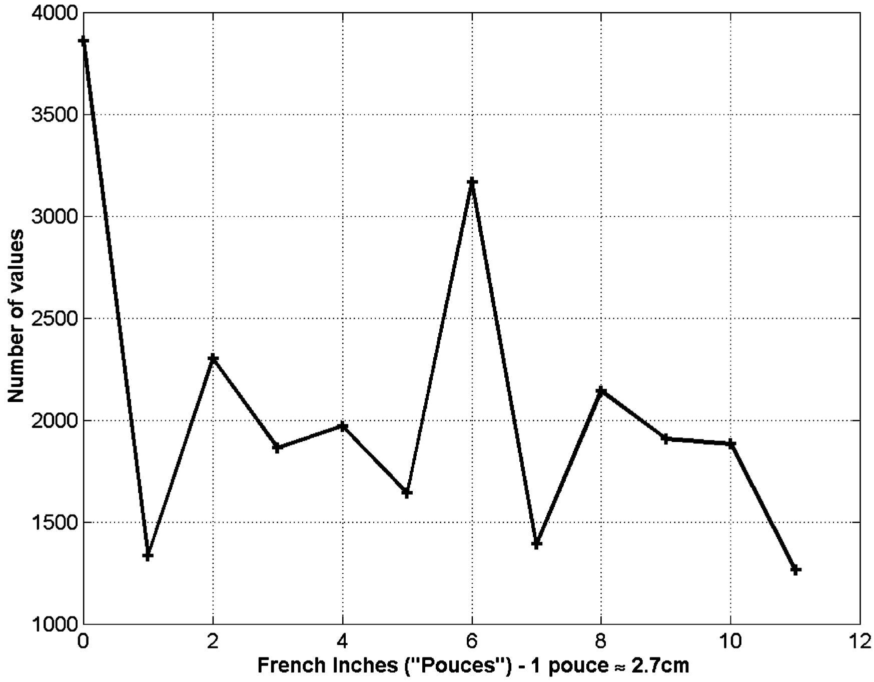


Fig. 9 Distribution of inch values of the feet in the 1757–1792 record at Brest

estimated to be 1.11±0.07 and 1.11±0.06 mm/year, respectively, over the 1846–2005 time period. They obviously cannot be considered statistically different from one another. The errors are the formal errors of the linear regression. MTL may therefore be used as a proxy for MSL, wherever HLW levels are available to compute this quantity.

Discussion on sea level trends

The eighteenth century data sets unfortunately cannot yet be considered in the discussion on the long-term sea level trends at Brest. We have partially succeeded in connecting these early data sets to the common datum of the modern time series starting in 1807 by analysing the documentation of several historical libraries. But the findings have to be qualified with reservations concerning the datum connection. The eighteenth century data initially seem a bit low in Fig. 3. The uncertainties could potentially be as large as 0.08–0.16 m (quarter to half of a foot). This issue needs further investigation (see "Datum reconstruction" section). We therefore concentrate hereafter on MTL. Their values for the period 1807–2004 are available and may be used as proxy for MSL (see "Significance of MSL and MTL trends" section).

Figure 3b definitely shows a sea level increase, which obviously cannot be characterised by a simple linear trend. The sea level acceleration is estimated at 0.0071±0.0008 mm/year^2 over the period 1807–2004 using a simple quadratic least-squares adjustment. The value is slightly higher with respect to the previous estimations carried out by Woodworth (1990) or Douglas (1992), but they still are consistent within a statistical 95% confidence level. We considered also the additional 20-year period 1985 onwards. Sea level appears to rise even faster over this period. Three linear trend periods can indeed be distinguished in the Brest MTL time series over the period 1807–2004:

(a) 1807–1890, over which the sea level rate is estimated at −0.09±0.15 mm/year
(b) 1890–1980, at +1.3±0.15 mm/year
(c) 1980–2004, at 3.0±0.5 mm/year

The errors are formal errors from the least squares linear regression. The RMS of the residuals are 0.03, 0.04 and 0.015 m. The location of the 'inflexion points' may appear somewhat arbitrary. We chose the ones for which the linear trends best joined together. The sea level trend of 3 mm/year over the last two decades appears significantly in excess of the longer period of 1890–1980. We implicitly assume here that the vertical land movement contribution is approximately linear over the last two centuries. Thus, this effect cancels out when comparing relative sea level trends from a single location over different periods. The assumption is consistent with geological evidence: The bedrock upon which the tide gauge is directly settled is a 'granit of Saint-Renan', a very resistant one according to Prof. Diot, geologist (personal communication). A sea level trend of 2.7±0.9 mm/year is obtained over the reduced period of 1993–2004. This figure, however, is not statically different from 3.0±0.5 mm/year over the longer period of 1980–2004. Both estimations fit closely with radar altimetry results over the last decade (Cabanes et al. 2001; Leuliette et al. 2004). Our results support the findings of Holgate and Woodworth (2004) of an enhanced coastal sea level rise during the last decade compared to the global estimations of about 1.8 mm/year over longer periods (Douglas 1991, 2001). The question as to when the relatively large global sea level trends observed in the twentieth century started is not accurately answered yet (Warrick et al. 1996). The second half of the nineteenth century is cautiously suggested. Our findings point out to an inflexion point at around 1890 at Brest, which is remarkably close to that in 1880 found in the Liverpool record by Woodworth (1999b).

Conclusions

New sea level records from the port of Brest from the eighteenth century, spanning several decades (1756–1792), have been discovered recently. Within the scope of this study, numerous smaller records that were thought lost have been found for the port of Brest, including the original records of HLWs covering 1807–1837 or the tide gauge data of 1846–1857. Most have been converted into modern digital form and stored in computer databases.

The quality of the former data has been investigated by editing and analysing the residuals between the tidal predictions and the observations. Although time-consuming, the approach has proved worthwhile in identifying measurement errors and subsequently correcting them where appropriate, even for data that were previously thought valid. For instance, several years of data published at PSMSL were identified as those corrected for the barometer effect in the tabulated data registers at SHOM, years 1937, 1939 to 1943.

The sundial correction of data prior to August 8, 1714 has been reviewed using the same data quality approach. A refined correction based on sundial literature (Savoie 2001) is proposed, which eliminates the systematic effects seen in the time residuals of the sea level heights. The tidal analysis has also shown that shallow-water tidal harmonics at Brest cause a systematic difference of 0.023 m between MSL and MTL. The study of the trends in MTL and MSL however indicates that MTL can be used as proxy for MSL.

Once the remaining historical libraries are searched, the digitisation of the data completed and their quality assessed, we hope to further investigate trends in sea level components at Brest over a 300-year period. The data sets will of course be made available within the free data policy of the French sea level data centre through its public access (http://www.sonel.org).

Woodworth (1999b) forecasted that other exercises of data archaeology would repay the efforts involved in both tidal data and historical documentation analyses. To conclude, may we forecast that the research activities of Christian Le Provost in sea level modelling and observation will be acknowledged by future generations of data archaeology researchers as we today acknowledge personalities like Picard, LaHire, Coubard, Cassini and Laplace for the work they did a few centuries ago?

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