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Changes in mean sea level around Great Britain over the past 200 years

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ABSTRACT

We systematically assimilate a wide range of historical sea level data from around the coast of Great Britain, much of it previously unpublished, into a single comprehensive framework. We show that this greatly increased dataset allows the construction of a robust and extended Mean Sea Level curve for Great Britain covering a period of more than two centuries, and confirms that the 19th century trend was much weaker than that in the 20th century and beyond. As well as attempting to maximise the amount of newly recovered sea level observations, we have also recovered the levelling metadata necessary to connect this 19th and early 20th century data with modern records. We adjust this data for known sources of variability and estimate overall uncertainties over the entire period. Data are processed in 36 regional clusters, before recombining to compute national statistics. We investigate the advantages of extending and adjusting the time series on sea level rise trends and low order variability. Confidence limits are improved by better than 60%. The weighted linear trend since 1900 for the fully adjusted data points from all clusters when averaged annually and adjusted for Glacial Isostatic Adjustment is 2.12 mm/year ± 0.02 mm/year (1-sigma). The much lower trend estimated for the 19th Century alone is 0.24 ± 0.12 mm/yr. There is an acceleration of 0.012 mm/yr^2 ± 0.003 mm/yr^2 in the rate of rise over the period 1813 to 2018. These trends are quite sensitive to the GIA correction used, but their differences and accelerations are not.

1. Introduction

The observational evidence thus far suggests that UK sea level rise (SLR) was low during the latter third of the 19th Century (Woodworth et al. 1999, Woodworth 2018), followed by a change in slope leading to about 1.4 mm/yr average rate of rise through the 20th century (Woodworth et al., 2009a,b), and an accelerating rate averaging 2.39 mm/yr since 1958 (Hogarth et al. 2020). This is consistent with a small number of European gauges with long records (Brest, Cuxhaven, Amsterdam/Den Helder; Woodworth 2018). However, these conclusions are mainly based on the UK continuous tide gauge record which is limited prior to about 1954, and before the 20th century is dependent on a very small number of gauges with discontinuous temporal coverage.

Woodworth (2018) showed that short tide gauge records with good datum control from the First Geodetic Levelling of the UK by the Ordnance Survey in 1858–59 when differenced with nearby modern measurements, could give valuable information on the mean trends over that interval, which was generally supportive of the above interpretation. A number of suggestions were made about how to exploit such information further.

In parallel, Hogarth et al. (2020) performed a data archaeology exercise which led to improved datum control and extension of a large number of UK records, and established that the records could be considered to consist of a seasonal cycle, a component driven by local atmospheric forcing, a linear trend associated with GIA, and a Common Mode which is uniform around the UK, as well as small residual local sea level variations.

In this study we use the same techniques as Hogarth et al. (2020) to extend and improve the Permanent Service for Mean Sea Level (PSMSL) dataset (Holgate et al. 2013) before 1958, and undertake a further extensive data archaeology exercise in order to greatly expand the sources of early data in the style of Woodworth (2018). We introduce a large number of early, short duration records associated mainly with Admiralty surveys, many of which have not been previously accessed. We then partition this data into 36 localised clusters around the UK, enabling us to extend and densify the early UK instrumental sea level record, confirming the low trend in that early period, and providing more robust measures of the time series back to the early 19th century.

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All data used is derived from at least daily observations (usually high and low waters) averaged over periods of at least a fortnight (semi-lunation). We use the following terminology:

"Continuous" data refers to time series of annual averages of monthly mean data from long term sea level monitoring sites, as traditionally used by the PSMSL.

"Campaign" data refers to sea level averaged over shorter term survey periods, from portable tide gauges levelled in to fixed land based reference points such as bench marks. These include episodic surveys carried out by the Admiralty, the coverage of which can range from two weeks to over a year, and the series of observations by the Ordnance Survey (OS) during the 19th Century.

"Newly assimilated" data means all of the campaign data (including the OS data used by Woodworth 2018), plus any continuous data that has been made usable by newly-recovered datum control information. The latter, in the manner of Hogarth et al. (2020) allows the formation of an extended version of the PSMSL RLR dataset which is referred to here as the Metric Extended Reduced (MER) record.

A particularly important source of information for this study came from the UK Admiralty archives in the form of the Admiralty Tidal Ledgers and Admiralty Datum Ledgers kept at the UK Hydrographic Office in Taunton, which contain detailed information on a range of sea level measurements and the associated datums.

In brief, the sources of newly assimilated sea level data (equivalent of 3348 station months) used in this paper are:

1. Continuous observations from fixed gauges at Naval Dockyards at Sheerness, Plymouth, Portsmouth and Pembroke. Annual means for several years are derived from twice daily HW and LW readings between 1832 and 1834, or for Sheerness, 1832 to 1843 and 1870 to 1894.
2. Campaign data from Admiralty sources such as the Tidal Ledger (supplement 2), covering 168 sites from 1834 to the 1950 s; data published by the International Hydrographic Bureau (IHB; now the International Hydrographic Organization), and data included on Admiralty Charts. Time spans range from 2 week surveys using portable tide gauges to segments of over a year extracted from longer records which existed at the time.
3. OS campaign data (19 sites from 1859 with spans of around two weeks, and 13 other sites with earlier dates, plus sites from 1896) these are covered in detail in Woodworth (2018).
4. Continuous data from "permanent" gauges published in various historical documents which has not yet been assimilated into the PSMSL records.
5. Short term campaign data from civil engineering, scientific, and harbour surveys.
6. 21st Century data from nine recently installed tide gauges not currently included in the PSMSL, including Blyth, Buckie, Cromarty, Inverness, Oban, Scarborough, Shoreham, Stranraer and an additional gauge at Whitby. These aid comparison with early data from these sites.
7. Unpublished data and metadata recovered from the National Oceanography Centre (NOC) archives in Liverpool (PSMSL and British Oceanographic Data Centre (BODC) archives).

By spatially clustering these new data sources, the temporal span of data available at almost all 36 clusters now exceeds a century. Overall an extra 1635 station-months or 136.25 equivalent station-year datapoints are added prior to 1900; 833 station-months or 68.7 station-years of these are prior to 1858. These include multi-year records in the 1830 s from the four Naval Dockyards at Sheerness, Portsmouth, Plymouth and Pembroke Dock.

Sea level relative to local land based reference points (RSL) as recorded by a perfect tide gauge (TG) is influenced by a combination of factors including local tide and meteorological effects, distant ocean variability and vertical land motion (Rossiter 1967, Thompson 1980, 1981). Tide gauges (and observers) are however imperfect, and this results in additional variability in the TG records caused by discontinuities in recording methods (e.g. changes from daylight only to 24 h observations) (Woodworth 2016) or instrumentation or datum control errors (Lennon 1971), causing false level changes or steps in the record, (Haigh et al. 2009). This last factor has been shown to be a significant source of low frequency variability, requiring correction even in modern data (Hogarth et al. 2020). Adjusting for these factors results in more consistent RSL records. Considering the UK sea level data from 1958 to 2018, the impact of any individual residual gauge error can be reduced by averaging simultaneous observations from a number N of different sites, by a factor of 1/sqrt(N). Extending the time series is also important as errors in linear trend due to a step-like datum error of given magnitude will reduce as the record length increases, the relationship approximating an inverse power law. Whilst this paper focuses on extending the dataset for the British Isles, a region in Northern Europe where there are already a high proportion of long time series, the methodology may prove useful for other regions which are poorly represented in the existing PSMSL dataset. The data archaeology has already revealed archived data from many global sites which has not yet been digitised and assimilated.

Tide gauge data are often reported relative to a national datum; a nominally level surface, determined by levelling between sites. It is now known (Penna et al. 2013) that this is prone to decimetre-scale errors at the scale of Great Britain (GB), and the periodic relevelling exercises and changes of chosen reference will introduce artificial time dependence in the sea level record. However, levelling over shorter distances is much more reliable, as shown below, and probably not the major error source. Accordingly, we group the measurements into 36 local clusters, within which we consider levelling errors to be small, so that sea levels can be directly compared from site to site and subsequently combined in optimal ways. A significant component of the work presented here is the correct identification of the relationship between the reported reference level of sea level data, and local benchmarks, so that all can be considered relative to a modern, consistent datum.

Sections (2) and (3) of this paper cover the sources of data used: (2) gives the sources for currently available Mean Sea Level (MSL) and the data required for adjusting the MSL records, and then (3) gives details of the sources and availability of the newly assimilated sea level measurements from the early 19th Century onwards around the coast of GB. Section (4) describes the data processing including adjustments and quality control checks, and discusses the uncertainties. The data is then partitioned into localised clusters, each around a central station for which recent MSL data are held by the PSMSL. All adjusted values within a cluster are treated as a set, and trends within each cluster are computed independent of other clusters. Table 4 in the appendix summarises the useable data sources, adjustments and uncertainties. Section (5) describes the results of the analysis. We then estimate the vertical offsets between different clusters by comparing the modern fully adjusted PSMSL (MER) records, and then apply these offset values to all older data within each cluster. This allows an overall annual average MSL for the British Isles to be estimated over a 200 year period. Section (6) discusses these results and quantifies how the additional data provides independent confirmation of sea-level rise acceleration, briefly considering adjustments for vertical post-glacial crustal movements and Section (7) concludes and discusses directions for further work.

2. Data sources

The sources of information considered for this paper are restricted to GB (England, Scotland, Wales and some island sites). Similar studies could be undertaken for other countries, notably Ireland for which many of the sources are identical.

2.1. Existing sea level data

The PSMSL is the main global data repository for continuous MSL time series (Holgate et al. 2013), https://www.psmsl.org/data/. The PSMSL datasets are available as "Metric" (monthly means only), regularly updated by national monitoring authorities around the world, and Revised Local Reference (RLR, monthly and annual means) based on the Metric data, but with quality control applied by the PSMSL as far as possible. The Metric data is usually referenced to the elevation of the tide gauge zero (TGZ), which may be altered occasionally, for example as instruments were replaced. For many sites, the PSMSL have records of these TGZ elevation changes relative to fixed "permanent" bench marks. This allows the sea level data to be referenced to a consistent land-based datum as part of the quality control, which the PSMSL define as "RLR". In the UK the RLR elevation is also linked through bench marks to local values of the National levelling datum, Ordnance Datum Newlyn (ODN), based on the MSL at Newlyn between 1915 and 1921 (Bradshaw et al. 2016), and usually to the Admiralty Chart Datum (ACD) which is based on some definition of local low water relative to ODN as used for Nautical Charts. Whilst the PSMSL holds some examples of 19th and early 20th Century RLR data from sites such as Liverpool and Sheerness, recovered retrospectively after the Service was set up in 1933 (IAPO 1939, 1958), the number of sites with long records suitable for trend analysis is limited (see Fig. 5 for locations with more than 40 years of PSMSL data). Around 15 recording gauges were operating in 1911 (Henrici 1911), and only 9 permanent tidal observatories were recorded around the GB coastline in 1902 (SOI 1905). Only five of the GB PSMSL RLR series contain more than 100 years of data with more than 75% completeness: Newlyn, North Shields, Aberdeen, Liverpool and Sheerness. The Sheerness PSMSL RLR series has the longest span, but several gaps. The Aberdeen, Liverpool, and North Shields series are effectively composite series using close but not exactly co-located sites. Three RLR sites have data from prior to 1895, two prior to 1862, and only one has data (Sheerness, 15 station-years) prior to 1858.

To maximise record length, we consider Metric data from the PSMSL from the earliest date available at each site up to the end of 2018. For example the Metric dataset contains additional published 19th Century monthly Mean Tidal Level (MTL; the average of high and low tides) for Holyhead, (Beechey 1848), and Milford Haven and Dundee (Thompson 1915). We are now able to adjust much of this data so that it is referenced to local ODN using newly recovered datum offset values, effectively applying RLR style adjustments. This is an extension of the work described in Hogarth et al. (2020) using only slightly modified methods to recover and adjust information before 1958. The limited number of extended annual results are added to the "newly assimilated" data (section 3).

2.2. Meteorological data

One-degree gridded monthly and daily mean sea level pressure (MSLP) and u and v wind components from 20CRv3 (Slivinski et al. 2019) were downloaded from: https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV3.monolevel.html

Five-degree gridded monthly MSLP (Luterbacher et al., 2002) for the Eastern North Atlantic and Europe (ASCII: slp_1659-1999.txt) was downloaded from:

ftp://ftp.ncdc.noaa.gov/pub/data/paleo/historical/north_atlantic.

2.3. GIA model data

The Peltier ICE-6G_C (VM5a) GIA model data (Peltier et al. 2015; Argus et al. 2014) for all PSMSL sites was downloaded from http://www.atmosp.physics.utoronto.ca/~peltier/data.php. The correction we apply includes gravitational effects due to the changing ice mass loads on the solid Earth since deglaciation and the resulting modifications to the gravity field as well as vertical land movement, removing the secular component of RSL that results from GIA. For sites not in the PSMSL we interpolate the 0.2 degree gridded GIA dataset dsea.12mgrid.nc also available from http://www.atmosp.physics.utoronto.ca/~peltier/data.php. We also checked agreement between grid derived values and those given for the PSMSL sites.

3. Newly assimilated sea level data

Improvements were made to the PSMSL data holdings by using the methods described in Hogarth et al. (2020), where the datum levels for additional Metric data as well as datum step errors have been systematically identified and resolved wherever possible. This MER dataset shows reduced variability for post 1958 PSMSL data, but here the results are extended over the entire observation period at each site, and such extensions are considered as 'new' data, for example we have recovered the 19th C datum information for Holyhead (Hawkshaw 1873; Thomson et al. 1879) as well as Neyland (Milford Haven) and Dundee (Thompson 1915), allowing this data to be included. Details of the new data, metadata and various adjustments are summarised in Table 4.

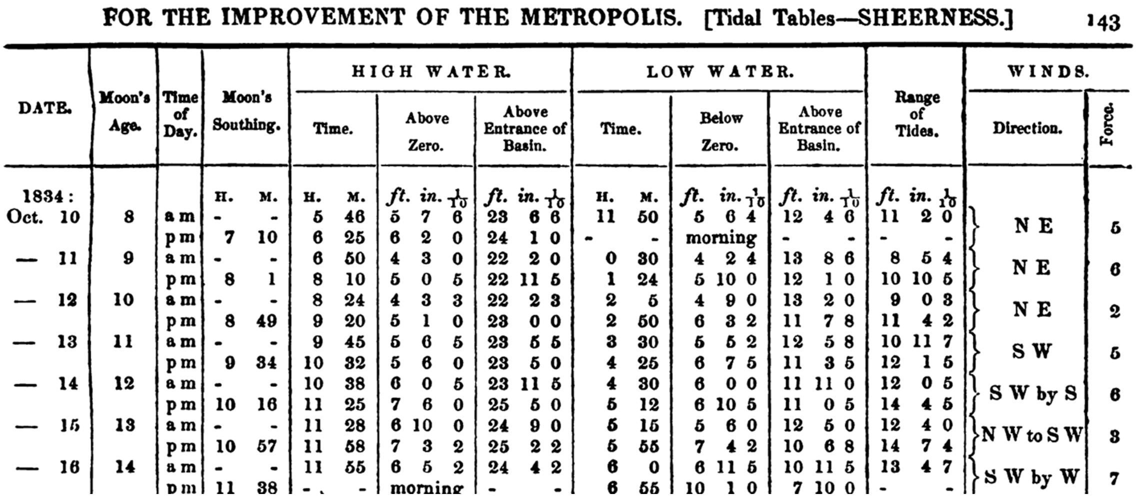
3.1. Admiralty dockyards

Lloyd (1831) gives details of setting up and levelling a tide gauge at the Admiralty dockyard at Sheerness in the lower Thames Estuary in March 1830. Lloyd's gauge registered HW and LW only, but was modified by Mitchell the Dock Engineer so that by September 1831 it was self-registering (Anon, 1832), on similar principles to the gauge proposed earlier that year by Palmer (1831). Lloyd also gives mean annual levels for high water and low water for 1827, 1828 and 1829 as well as monthly MTL for 1827 read manually from the tide scale carved on the stone of the dock caisson. The zero reference of this scale was the level of the paved entrance of the dock. Lloyd used the 31 foot mark on the same scale to give a tidal reference point and connected this to several bench marks he set up (Bevans 1832) (e.g. http://www.bench-marks.org.uk/bm27754). Some of these still exist and were later re-levelled by the OS. The tide gauge zero was set to "18 feet" above the dock entrance. This was actually 17 feet and 11 in. in the hand written tidal register of HW and LW (Bradshaw et al. 2015), which was close to the observed MTL (see below). Thus the recorded sea level and the original stone tide scale zero can be connected to the modern ODN.

The Admiralty also installed similar automatic gauges at other Dockyards: Portsmouth, Plymouth (Walker 1846) and Pembroke. In addition to the original mareogram records, each HW and LW (night and day) was manually recorded in tidal ledgers. Tables of these twice daily HW and LW were published by the Royal Society (Admiralty, 1833) and the Admiralty (Anon, 1835). Until now, this data has not been systematically analysed. The original tabulated data, 1832–34, is held in the Royal Society library, and in the Admiralty Library in Portsmouth Dockyard. Tabulated daily measurements from Sheerness for the extended period 1832 to 1843 were also published in the report of the Metropolis Improvement Commissioners (Anon 1845). These were also referred to the entrance of the dock as well as the TGZ, which resolves any ambiguity about the gauge zero setting over this period (Fig. 1)

The details of these twice daily measurements, which record the times and heights of high and low waters, are summarised in Table 1.

The MTL values we derive here are computed independently by digitising these original tidal ledgers. For Sheerness, this gives us several years over which we can directly compare MTL to existing MSL records. We can then use this information to fill some of the large gaps in the coverage of the current MSL series with additional monthly data from various sources, for example we have also digitised the daily tidal ledgers from Sheerness (HW and LW) from 1870 to 1894 (this may be duplicating earlier work; Rossiter (1972) plots some annual values, hand written versions of which we have found in the archives), and the ledger containing a year of daily data from 1930 (scanned images of these original hand written ledger pages recently made available from the



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DATE.	Moon's Age.	Time of Day.	Moon's Southing.	HIGH WATER. Time.	HIGH WATER. Above Zero.	HIGH WATER. Above Entrance of Basin.	LOW WATER. Time.	LOW WATER. Below Zero.	LOW WATER. Above Entrance of Basin.	Range of Tides.	WINDS. Direction.	WINDS. Force.
1834:			H. M.	H. M.	ft. in. 1/10	ft. in. 1/10	H. M.	ft. in. 1/10	ft. in. 1/10	ft. in. 1/10		
Oct. 10	8	a m	- -	5 46	5 7 6	23 6 6	11 50	5 6 4	12 4 6	11 2 0	N E	5
		p m	7 10	6 25	6 2 0	24 1 0	- -	morning	- -	- -		
— 11	9	a m	- -	6 50	4 3 0	22 2 0	0 30	4 2 4	13 8 6	8 5 4	N E	6
		p m	8 1	8 10	5 0 5	22 11 5	1 24	5 10 0	12 1 0	10 10 5		
— 12	10	a m	- -	8 24	4 3 3	22 2 3	2 5	4 9 0	13 2 0	9 0 3	N E	2
		p m	8 49	9 20	5 1 0	23 0 0	2 50	6 3 2	11 7 8	11 4 2		
— 13	11	a m	- -	9 45	5 6 5	23 5 5	3 30	5 5 2	12 5 8	10 11 7	S W	5
		p m	9 34	10 32	5 6 0	23 5 0	4 25	6 7 5	11 3 5	12 1 5		
— 14	12	a m	- -	10 38	6 0 5	23 11 5	4 30	6 0 0	11 11 0	12 0 5	S W by S	6
		p m	10 16	11 25	7 6 0	25 5 0	5 12	6 10 5	11 0 5	14 4 5		
— 15	13	a m	- -	11 28	6 10 0	24 9 0	5 15	5 6 0	12 5 0	12 4 0	N W to S W	3
		p m	10 57	11 58	7 3 2	25 2 2	5 55	7 4 2	10 6 8	14 7 4		
— 16	14	a m	- -	11 55	6 5 2	24 4 2	6 0	6 11 5	10 11 5	13 4 7	S W by W	7
		p m	11 38	- -	morning	- -	6 55	10 1 0	7 10 0	- -		

Fig. 1. An extract of the tabulations for Sheerness: high and low water times and heights, wind direction and force.

Table 1
summary of available data from four Admiralty dockyards. 1 in. = 25.4 mm.

Dockyard	Latitude (degrees N)	Longitude (degrees E)	Start	End (inclusive)	Resolution
Sheerness	51.446	0.743	Jan 1832	Dec 1843	0.1 in.
Sheerness			Jan 1870	Oct 1894	1.0 in.
Sheerness			Jan 1930	Dec 1930	1.0 in.
Portsmouth	50.802	−1.111	Jun 1832	Dec 1834	0.1 in.
Plymouth	50.368	−4.185	Jun 1832	Dec 1834	0.25 in.
Pembroke Dock	51.692	−4.944	Nov 1832	Dec 1834	1.0 in.

BODC). We have also digitised around a month of HW and LW measurements from Sheerness from 1856 (Redman 1877b), as well as some data from 1952. We have also added the manually recorded monthly MTL data (calculated from daytime only observations at the same dock caisson tide scale used by Lloyd) from 1827 (Lloyd 1831) in order to create a more complete monthly time series. The annual average (or seasonally adjusted and weighted average of sections shorter than 12 months) of this new monthly dataset is used to create an extended annual time series for Sheerness. This is further extended with addition of old published annual mean values, derived from original records which may no longer exist (e.g. (Lloyd 1831) gives annual values for Sheerness for 1828 and 1829).

In summary we have digitised all the tabulated HW and LW data for the periods in Table 1 as well as available data from historically published analyses. This involved more than 136,000 spreadsheet entries. Most entries were transcribed independently by the first two authors, then compared. The handful of individual discrepancies were then investigated and resolved. Each time series was also checked visually, which allowed us to resolve a small number of 19th Century transcription errors.

The Portsmouth, Plymouth and Pembroke Dock daily measurements were also recorded at least to 1838 and results were published by the Admiralty (1839). These were cited in the First Geodetic Levelling (FGL) report of the Ordnance Survey (James 1861a,b). To date no copy of these observations has been found, but the OS report does give MTL values averaged over the four years 1835 to 1838 for these three sites (James, 1861a,b). In addition, for Plymouth, tables of annual MHW and MLW for 1833 to 1838 as well as annual mean levels were published (Whewell 1839) derived from these original records.

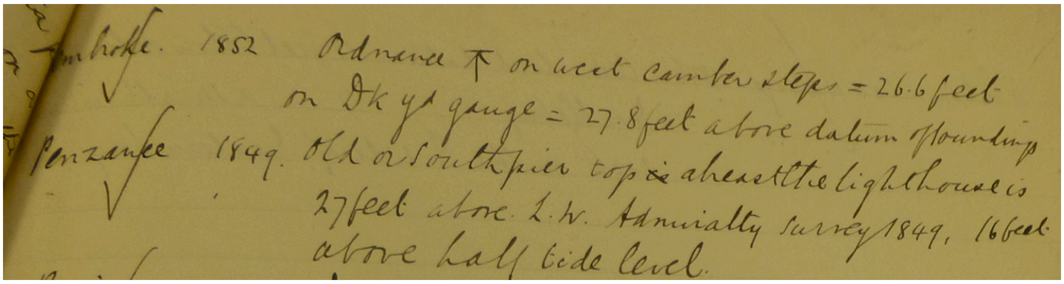
The zero level for these gauge measurements referenced to local bench marks can be recovered from information in the Admiralty Datum Ledgers (Fig. 2 and see Appendix 1 for details) and from notes in the published Admiralty tide records. Hence, annual average MTL data from 1832 to 1838 referenced to local datums for these dockyard sites has now been recovered. Fig. 5 shows the Dockyard locations. Fig. 11 shows the simultaneous monthly MSL values for the four Dockyards.

3.2. *Admiralty short term "campaign" surveys*

The Hydrographic Office Archives in Taunton contain hand-written ledgers of Tidal Levels and Datums recorded during short term hydrographic surveys for the Admiralty Charts which were carried out to best survey practice guidelines (Admiralty, 1862; Hydrographer of the Navy, 1969). A typical example from the Tides Ledger (Fig. 3) shows Admiralty parameters for Padstow, Cornwall.

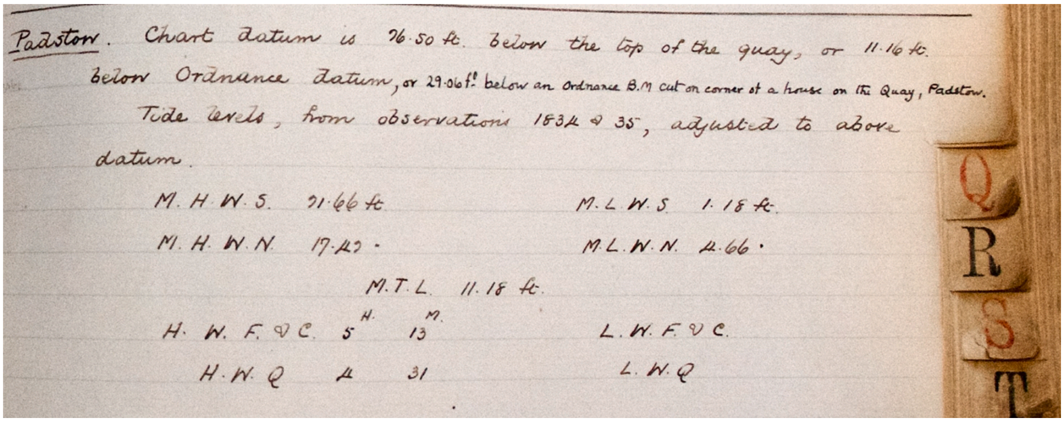
It gives datum levels to a local bench mark, and states this is 11.16 feet below Ordnance Datum. The summarised calculations are based on observations from 1834 and 1835. The MTL is recorded as 11.18 feet referenced to the Chart Datum in 1834–5. Spring and Neap High and Low Water levels are additionally calculated and tabulated. So are the High Water Full and Change times of High Tide after lunar transit, that is at times of Full and New Moon. H.W.Q. is the time delay after transit for Lunar Quadrature. These traditional terms are now seldom used. There is no information in this entry of the times of year the measurements are made so a correction for seasonal variations cannot be made. Many entries do have this seasonal information, and can be adjusted.

In total, the Tidal ledger has 168 entries for individual ports plus six in Ireland and two in the Channel Islands, as shown in Fig. 5. The observation periods are at least a single lunation (around 15 days) but in some cases extend to several years. The observation dates range from the 1830 s to the late 20th Century as the chart datums were intermittently revised. Several other ports are up previously-navigable rivers; these include many ports which cannot be used here because values or datums were derived by comparison with water level observations at the coastal sites. A full list is given in Table S2 which shows how these ports are now numbered in the annually produced Admiralty Tide Tables (ATT). The order is as in the ATT listings, following the convention of anticlockwise numbering around Britain from the Scilly Isles in the southwest. We use this convention in this paper. Several of the ports in supplementary Table S2 have declined in importance and are no longer listed in the annual ATT publications. In a small number of cases copies of the tabulated daily records of HW and LW which relate to the summaries in the ledger have been stored in the PSMSL archives (e.g. daily HW and



Pembroke. 1852 Ordnance ⤒ on west camber steps = 26.6 feet
on Dk yd gauge = 27.8 feet above datum of soundings
Penzance 1849. Old or South pier top is abreast the lighthouse is
27 feet above L.W. Admiralty survey 1849, 16 feet
above half tide level.

Fig. 2. Extract from the Tidal Ledger Volume 1, showing the earliest entry for Pembroke Dock (top). "Pembroke. 1852 Ordnance ⤒ on west camber step = 22.6 feet on Dock Yard gauge = 27.8 feet above datum of soundings" (depth on charts). The arrow and bar symbol refers to a bench mark, in this case set by the OS in 1841. There are several updates for Pembroke later in the Ledger. This information should be used in conjunction with the date of the tidal observations in order to ensure the correct tide gauge zero and bench mark elevations are used.



Padstow. Chart datum is 26·50 ft. below the top of the quay, or 11·16 ft. below Ordnance datum, or 29·06 ft. below an Ordnance B.M cut on corner of a house on the Quay, Padstow.
Tide levels, from observations 1834 & 35, adjusted to above datum.

M.H.W.S. 21·66 ft. M.L.W.S. 1·18 ft.
M.H.W.N. 17·42. M.L.W.N. 4·66.
M.T.L. 11·18 ft.
H.W.F.&C. 5 H. 13 M. L.W.F.&C.
H.W.Q 4 31 L.W.Q

Q
R
S
T

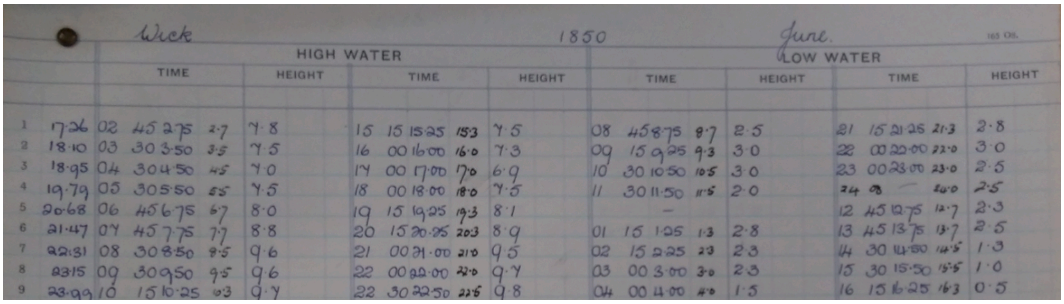
Fig. 3. Example of entry in the UKHO Tidal Ledger, here showing summary of tidal information for Padstow. The MTL values were derived from observations of high and low waters recorded during Admiralty Survey campaigns, and were linked to OS bench marks. The information was often printed on local Admiralty Charts.

LW data from Wick recorded in April, May and June 1850), Fig. 4.

The International Hydrographic Bureau (IHB), through the mid-twentieth century, issued a series of loose-leaf sheets of tidal analyses including MTL or MSL information, worldwide. These values were supplied by each National Hydrographic Authority, in the case of Great Britain this was the Hydrographic Office. Almost all the UKHO Tidal Ledger information also appeared in the IHB series; we have scrutinised all these sheets and found additional ports and information which is not in the Ledger. Some of the large-scale Admiralty Charts and the annual ATT also contain summaries and updates of tidal survey information or metadata not found in the Ledgers. Data from these various Admiralty sources are cross checked and included in our analysis. High resolution scanned images of Admiralty Charts for the coast of Scotland are freely available from: https://maps.nls.uk/coasts/admiralty_charts_list.html and help give additional information for the Northwest coast, which is otherwise sparsely represented in Fig. 5.

3.3. Ordnance Survey, first Geodetic levelling (FGL).

As part of the early 19th Century triangulation of the UK by the OS, a few MSL observations were taken in 1838 in Northern Scotland (Clarke and James 1858, pg. 552). Only one of these (Rispond) can be securely connected to later OS bench marks. From 1840 to 1860, the OS carried out the First Geodetic Levelling of England, Wales and Scotland (FGL). Levels were referred to a nominal value of MSL at Liverpool (Ordnance Datum Liverpool, ODL), which was estimated from measurements made over a few weeks in 1844 (Thomson et al. 1879, Jolly and Wolff 1922). Towards the conclusion of the FGL, sea level measurements from 32 coastal stations in England and Wales, and 18 stations in Scotland were connected to local bench marks which were referenced to ODL. (Table S1, Fig. 6 and James, 1861a,b). Most of these measurements were recorded by the OS over typically two weeks (average 15.8 days, approximating a semi-lunation at each site), using complete daytime



Wick 1850 June 165 OS.

		HIGH WATER										LOW WATER									
		TIME				HEIGHT	TIME				HEIGHT	TIME				HEIGHT	TIME				HEIGHT
1	17·26	02	45	2·75	2·7	7·8	15	15	15·25	15·3	7·5	08	45	8·75	8·7	2·5	21	15	21·25	21·3	2·8
2	18·10	03	30	3·50	3·5	7·5	16	00	16·00	16·0	7·3	09	15	9·25	9·3	3·0	22	00	22·00	22·0	3·0
3	18·95	04	30	4·50	4·5	7·0	17	00	17·00	17·0	6·9	10	30	10·50	10·5	3·0	23	00	23·00	23·0	2·5
4	19·79	05	30	5·50	5·5	7·5	18	00	18·00	18·0	7·5	11	30	11·50	11·5	2·0	24	08	–	24·0	2·5
5	20·68	06	45	6·75	6·7	8·0	19	15	19·25	19·3	8·1			–			12	45	12·75	12·7	2·3
6	21·47	07	45	7·75	7·7	8·8	20	15	20·25	20·3	8·9	01	15	1·25	1·3	2·8	13	45	13·75	13·7	2·5
7	22·31	08	30	8·50	8·5	9·6	21	00	21·00	21·0	9·5	02	15	2·25	2·3	2·3	14	30	14·50	14·5	1·3
8	23·15	09	30	9·50	9·5	9·6	22	00	22·00	22·0	9·7	03	00	3·00	3·0	2·3	15	30	15·50	15·5	1·0
9	23·99	10	15	10·25	10·3	9·7	22	30	22·50	22·5	9·8	04	00	4·00	4·0	1·5	16	15	16·25	16·3	0·5

Fig. 4. Example of tabulated record of twice daily HW and LW for Wick for June 1850, transcribed from the same original data as used to compute the summary MTL in the Tidal Ledger.

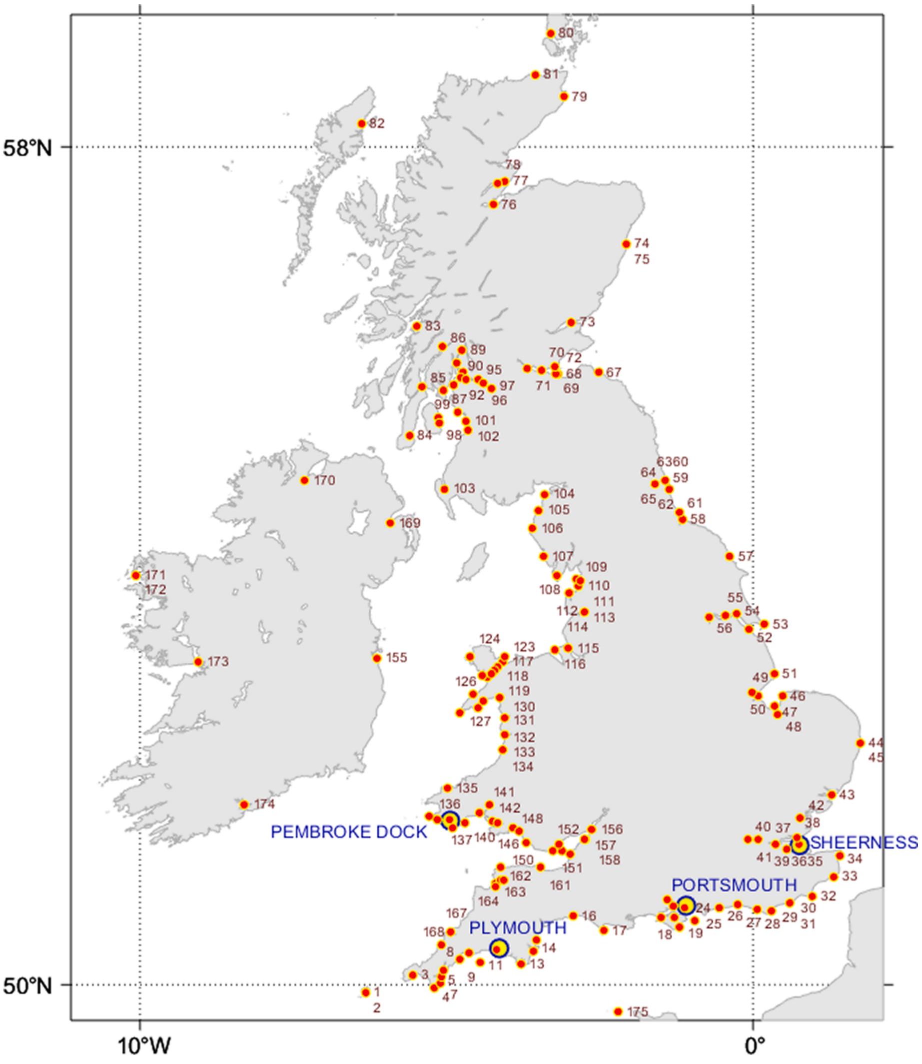


Fig. 5. Location of the four Admiralty Dockyards which have tide gauge records from the 1830s (blue open circles), and the sites of the harbours covered by the Admiralty Tidal Ledger where additional early tidal measurements are available (numbers refer to sites listed in Table 4).

tidal cycles (except for Sundays), observed at 10 min intervals. HW and LW times and heights were also recorded to within five minutes and in most cases, to a twentieth of a foot (around 15 mm). Ordnance Survey (1861a) also includes some data from additional sites, most importantly the means of the Admiralty 1835–38 data (see above). Crucially, in all cases the tide gauge zero was levelled to nearby bench marks to high precision.

This 1859 OS data was first analysed in detail from a 21st Century perspective by Woodworth (2018), who shows that these measurements are a valuable addition to the 19th Century sea level data base. We incorporate this 1859 OS data systematically into our analyses, including many of the adjustments applied by Woodworth. Woodworth uses the averages of the 10-minute daylight readings, considering missing night-time data and any additional observations beyond the start and end HW and LW turning points, which might otherwise bias the mean values. In one or two cases, notably at North Shields, the OS sea level measurements are given as an average over a complete year.

A summary of similar OS tidal measurements made in 1896 was published in 1899 (Anon. 1899), and a table giving MSL values to ODL and ODN and brief details are given in Jolly and Wolff (1922). We also include this data, however, as in Woodworth (2018), we were also unable to locate any documents giving the exact dates of the observations, and therefore we cannot adjust these 1896 observations for seasonal or meteorological variations. This leads to larger uncertainties being associated with these values. Fig. 6 shows the 1859 OS measurement sites as well as PSMSL sites with more than 40 years of data.

The Ordnance Survey also carried out local sea level referenced surveys on island sites such as the Scilly and Channel islands, the Isle of Man (Neely 1930), Orkney and Shetland Islands. For these sites a MTL datum was usually established at an early date referenced to a local benchmark. In many cases this local Ordnance Datum has remained in use.

3.4. Continuous observations not in the PSMSL.

Initial scientific analyses of tides were based on long series of manual observations from docks such as London and Liverpool (Lubbock 1830, 1835, 1836, Whewell 1836), but as these were often limited to HW observations only they are of limited use for MSL analysis. The installation of self-registering tide gauges was encouraged through the British Association for the Advancement of Science, and its sub-committees (Reidy 2009 gives a detailed summary). These provided continuous traces of the tidal variations, which were otherwise laborious to observe and record by hand even over a single tidal cycle. As well as the dockyard gauges, as early as 1833 a Mr Shirreff installed a self-registering gauge at Bristol after the pattern of Palmer and the records were published (Anon 1836), but without a precise datum (the bed of the river was referenced). This gauge was replaced by a much improved one

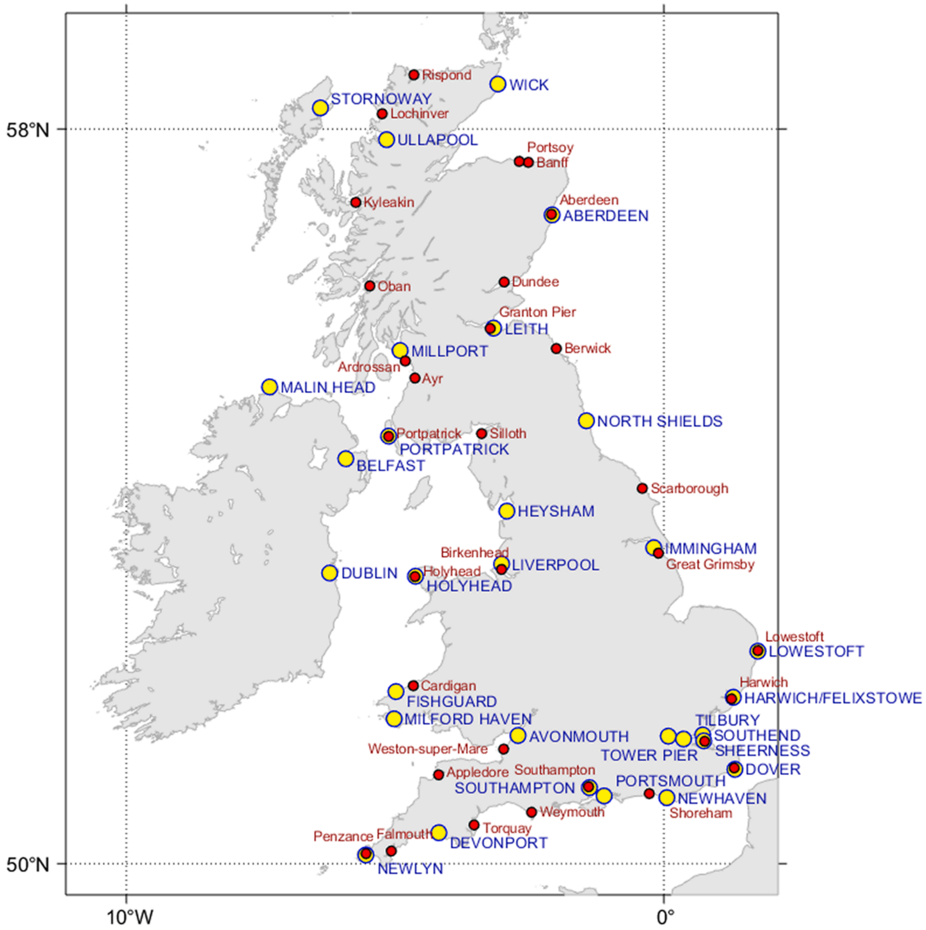


Fig. 6. Blue circles with yellow fill, sites from PSMSL and metric extended reduced dataset with more than 40 years of recent data, and red: sites where sea level measurements were made for the FGL, 1840 to 1860.

designed by Bunt in 1837 (Whewell 1838b, Bunt 1867). The data from Bristol is not used here as the site is too far upriver, but by the 1840 s, the ports of Harwich, Dover and Ramsgate also had automatic gauges installed. Scientists were able to obtain and analyse these records which extended over much longer periods than previously and publish their results.

Data from such results that we have digitised and been able to connect to ODN include 19th Century data from Hilbre Island and Ramsgate (Thomson et al. 1873), Hartlepool and the Humber (Oldham et al. 1863, 1865), Dover (Baird and Darwin 1885, Darwin 1888, Roberts 1913), London (Redman 1877a, 1877b, 1883, Shankland 1932), Liverpool (Webster 1848, Bevis 1851, Lord 1855, Henderson 1857, Parks 1857, Schoolbred 1876a,b, 1878, 1906), Dundee (Cunningham 1895), Hull, Grimsby (Shelford 1869), the Avon, (Mackenzie 1879), Clyde and Severn (Gibson 1938).

We also include additional segments of continuous data from the BODC and from other recently published research (Spencer et al. 1988; Haigh et al. 2009; Edmeades 2015). The data from Spencer et al. is available at https://www.psmsl.org/data/longrecords/ancill_rep.htm

We also include data from recently installed harbour gauges at Shoreham, Scarborough, Whitby, Blyth, Buckie, Inverness, Cromarty, Oban and Stranraer, (data from other sites is available, but only these gauges appear to record over the complete tidal range) and we have applied similar quality control to this high frequency data and calculated monthly mean and annual MSL (as well as HW, LW and MTL) values. The raw data can be found at https://www2.sepa.org.uk/waterlevels/ and https://riverlevels.uk/

3.5. *Campaign Survey data*

Other shorter series of observations were also the subject of published scientific analysis. A series of high frequency observations from Southampton and Ipswich were instigated and analysed by Airy (1843). Whewell recorded Bunt's levelling work between Axmouth and Portishead (Whewell 1838a), from which we were able to recover MTL for Axmouth and Portishead for short periods of 1837 and 1838 and Wick Rocks in 1838. Additional data can be recovered from historical civil engineering records. In 1813 daily high and low waters were manually recorded between 27th March and 3rd August 1813 at various points on the River Tyne (by Francis Giles under direction of John Rennie). A portion of this data (22nd April to 11th June 1813) was published (Brooks 1867) and has been digitised for North Shields for this paper. Importantly, the bench mark cut into the stonework of the North Shields New Low Lighthouse in 1813 as part of this survey has been used as a vertical reference point ever since. This is possibly the earliest UK data available where both daily Low Waters and High Waters are recorded where the original bench mark still exists and was in recent use. Historical summaries of other very early (pre 1820) MTL are available for Liverpool, Sunderland, and Portpatrick. Wherever the data span covers two weeks or more and a recovered tide measurement datum can be referenced to ODL or ODN, this data is included in the analysis (e.g. Wallis 1899, Shankland 1926). Some early high frequency manually observed MSL (often over separate spring and neap tidal cycles) has also been published (Beardmore 1852). Though too short to be included in this analysis, they can still provide useful datum and quality control information, particularly for any overlapping longer MTL series. Other continuous records are alluded to in some analyses, but either no data is provided or only short extracts are published (Robertson 1869 (Leith), Bowden 1956, (Shoreham 1953), Cartwright and Crease 1963 (Ramsgate 1957 and 1958)).

For background information, Ireland was surveyed through the 1830 s. Linked to this, the Ordnance Survey of Ireland measured sea levels at 22 sites in the summer of 1842, over two months, to fixed bench marks as part of their Irish mapping and levelling campaign (Airy 1845). Data from three sites, Courtown, Castletownsend and Ballycastle, have been compared with recent measurements (Pugh, 1982). Measurements in Ireland to fixed bench marks were continued in 1850 and 1851, by the Royal Irish Academy (Haughton, 1854; 1865). Irish data are not included in our analysis. An integrated analysis of Irish sea levels is underway.

4. Data adjustments and corrections

Table S3 in the supplementary material summarises the various factors to be considered.

Throughout, the term “adjustments” is used to describe processes where we attempt to reduce variability (formally statistical variance, though we often use standard deviations as a measure) in the observed sea level caused by factors like local meteorology. This is distinct from “corrections” where we attempt to remove external sources of error in the sea level records, such as incorrectly set TGZ. Comparing older sea level measurements with recent PSMSL values requires an understanding of how the instrumentation and analysis methods as well as the reference datums and local site environment have changed. The early data are almost always MTL in feet, and to ODL. These must be converted to metric units (we use mm), to MSL, and referenced to the same revision of ODN as used in the most recent tide gauge levelling. Many older measurements are for short periods, much less than a year, and an adjustment for the average seasonal variation is necessary, which is derived from a long series of quality controlled monthly MSL data from a suitable nearby site.

Major dredging campaigns, sand bar removal and pier construction from the mid-19th Century onwards have also affected tidal regimes upstream of the river mouths of several ports, so data from sites some distance from the open sea require careful assessment (Familkhalili and Talke 2016; Talke and Jay, 2020). In making these adjustments, it is important also to quantify the confidence with which each adjustment can be made.

When comparing the data from all sites (section 4.7), we make use of the understanding that corrections for datum errors are site specific and not correlated, adjustments for GIA and meteorological components are highly correlated locally, but can vary substantially around the country, whilst components due to more distant ocean variability are expected to be more consistent from site to site.

4.1. MTL to MSL

MTL, the average of High and Low Water heights over some defined period, is easily computed and so was generally favoured in the 19C and later. However, MTL is not the true MSL, obtained by averaging regularly sampled (typically hourly) levels over a period, and the difference can be as much as several centimetres. For a fuller discussion see Pugh and Woodworth (2014), Appendix C, and Woodworth, (2016). An approximate correction (in a predominantly semidiurnal tidal regime such as around most of the UK coast) can be calculated based on the amplitude of the M_4 constituent and its phase relative to that of M_2.

For many sites modern high frequency measurements (sampled every 10 or 15 min) over a number of years are available, allowing MTL and MSL to be derived directly from the data. The difference (including any nodal corrections (Woodworth 2012), see below) is systematic and can be assumed to hold for older data assuming the tidal regime has not changed. This observation based method is used where possible. For sites where high resolution data is not available, an estimate of MTL-MSL can also be found by directly synthesising a period such as a year of High and Low Water levels for a port from known tidal constituents, relative to a zero MSL. MTL-MSL is then the difference of the means from zero. This approach has been used here for some sites with predictions provided by Philip Woodworth, for the year 1989. Where the above methods are not possible, an estimate can be made using (MTL-MSL) values for the northwest European shelf plotted by Woodworth (2016). Some caution is required: as Woodworth (2016) shows, including a full set of higher harmonics such as M_8, can make a difference of a few tens of mm (21 mm for Liverpool), and these higher harmonics can be very locally generated. In many cases the exact location of the original measurements is not known, so uncertainty in this adjustment is increased. In addition, the assumption of an unchanged tidal regime may not hold (Mawdsley et al., 2015). Around the GB coastline, many harbour and river channels were altered by dredging campaigns in order to accommodate ever-larger vessels, again adding to uncertainties for sites some distance upriver. In column 7 of Table 4 the MTL adjustment values are given for many of the ports which are centres of clusters, a concept to be introduced in the next section. The average adjustment is −18 mm, with a mean absolute difference of 56 mm at individual sites. The adjustment is significant.

The 1859 adjustment (OS data, section 3.3) to be added to MTL ranges from −139 mm at Sheerness to 143 mm at Plymouth. However, it changes over a nodal 18.6 year tidal cycle. Fig. 1s in the supplementary material shows the changes based on annual predictions at Southend over the period 1829 to 1848. There is a 7.1% modulation, a range of 23 mm with the smallest difference, −138 mm in 1839, when the nodal factor is near a maximum, and the semidiurnal tidal range is least. The maximum difference, −162 mm is in 1829 and 1848. This is small compared with other uncertainties, so nodal adjustments are only made for Sheerness and Plymouth. The MTL to MSL adjustments (where used) are given in column 7 of Table 4 in the appendix.

4.2. Ordnance datum Liverpool to Ordnance datum Newlyn.

In order to reduce all MSL observations to a common datum, at least locally, we must account for any changes in datum over time. Very early 19th Century data was often referred to fixed local datum points such as a dock sill. Later in the 19th Century UK sea levels (and the older datums) started to be referred to ODL, which was transferred around the country during the First Geodetic Levelling (FGL), 1840 to 1860. Subsequent local relevelling meant that revisions were made to ODL bench mark elevations up to the 1900 s (Burnett and Carmody 1960). A Second Geodetic Levelling (SGL) was undertaken by the OS between 1912 and 1921, with ODN heights ultimately expressed relative to MSL at Newlyn from 1st May 1915 to 30th April 1921 (Henrici 1920, Jolly and Wolff 1922; Close 1922a, 1922b, 1923). The SGL was not extended to south-east England until 1946–51, and not to Scotland until 1936–1952. A Third Geodetic Levelling (TGL) 1951–1959 was adjusted to closely fit the elevations of the SGL Fundamental bench marks located every 50 km or so (Kelsey 1972). Hence, differences between ODN levels from the SGL and the TGL are usually small. The modern PSMSL GB RLR sea level measurements are referenced to a set of nearby TG bench marks connected to this third version of ODN.

Here, wherever possible, we resolve the local OD elevation differences in different time periods using documented levelling connections between individual benchmarks, thus allowing connection of the older sea level measurements to the latest revision of ODN. This allows for any network datum elevation changes due to local revisions in ODL or ODN, and allows preferential selection of stable bench marks near the tide gauge site. This differs slightly from the method of Woodworth (2018), who used the 1 km gridded conversion values provided at the OS website:

https://www.ordnancesurvey.co.uk/gps/legacy-control-information/liverpool-to-newlyn. Individual bench mark information to ODN is tabulated by the OS in one-kilometer grid squares for all of Great

Britain at: https://www.ordnancesurvey.co.uk/benchmarks. For each km square, this site gives details of bench marks: grid reference, mark type (e.g. cut mark, rivet, flush bracket) height in mm to ODN and previous datum revisions (sometimes including ODL), levelling order (First, Second or most commonly Third order of accuracy), year of leveling or verification, and the height of the mark above ground to ease relocation. Most bench marks on this list were last visited from 1950 to the early 1980 s. The ODN-ODL differences vary systematically and locally across Great Britain (Fig. 7).

The elevations of these and many other older bench marks not in this list were printed on large scale OS maps and town plans from the 19th and early 20th Centuries, from which we have extracted a significant amount of additional bench mark information. Elevations are usually given to a tenth of a foot but sometimes one-hundredth of a foot. These maps are freely available from the digitized collection of the National Library of Scotland at: https://maps.nls.uk/os/. Early OS maps as well as revised versions up to the late 20th Century (with elevations to the later revisions of ODN) are also available (for a monthly subscription fee) at: https://www.old-maps.co.uk.

In the UKHO tide or datum ledger a TGZ or ACD elevation is typically given in feet below one or more bench marks, as well as the bench mark elevations above ODL (or ODN). Even if the original bench mark no longer exists, a modern elevation to ODN can be estimated by comparing contemporaneous elevations of the original and nearby bench marks (taking care that such elevations are referred to the same ODL or ODN revision) provided some of these also have modern ODN elevations, or in turn can be connected to bench marks with modern elevation values. Confidence in these geodetic connections and adjustments can be increased by comparing many pairwise connections of bench marks with old and new elevation values.

Table S4 in the supplementary material shows the bench marks that had been levelled to both ODL and ODN for the four Admiralty Dockyard sites. Local inspection showed that several of these marks were extant and robust in 2016 and 2017, as indicated by an asterisk. The stability of the results is good, as indicated by the standard deviation of between 10 and 30 mm at all four sites. For Sheerness the bench mark at TQ 9169 7475 (in italics), where the difference is four standard deviations from the mean, is excluded as the mark has probably been displaced. Similarly, for Plymouth the bench mark at SX 3485 5469 across the River Tamar from the dockyard, was omitted.

Over one thousand bench marks with both ODL and ODN levelling were found at 90 coastal locations. At Pembroke Docks for example, 144 recorded elevation values were compared for 50 local bench marks (with 19 of these from the original 1841 and 1850 levelling). Conversely, only two usable bench marks were found for Kinlochbervie. Extensive port development, for example at Southampton, is a major limiting factor for long-term stable bench marks. The adjustment of ODL to ODN varied from subtracting 610 mm at Harwich, to adding 611 mm at Oban. A few rogue marks at other sites were excluded, and some local anomalies are discussed later, but overall the average standard deviation of the differences for groups of bench marks at a particular site was 21 mm. Adjustments to 20th C standards for our 19th C sites are included in column 8 of Table 4.

The small standard deviations at each site confirm the underlying

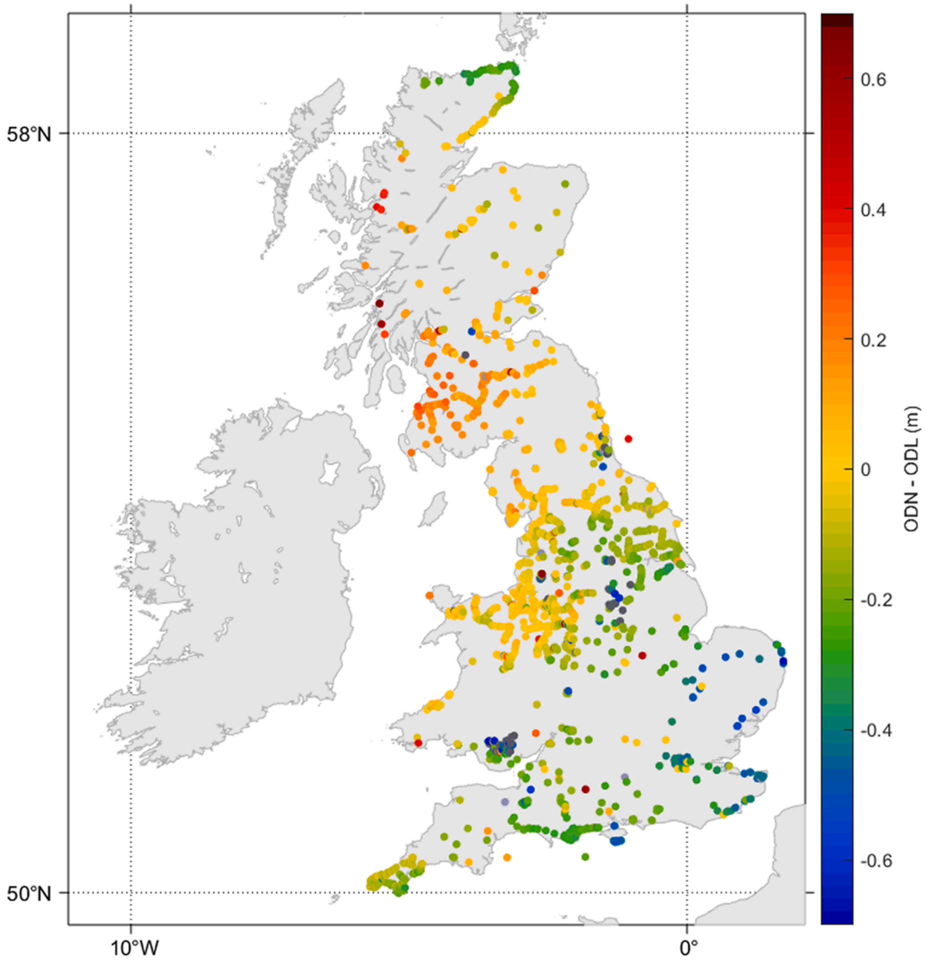


Fig. 7. Plot of ODN minus ODL elevation differences for all 3023 bench marks in the OS database which have both ODN and ODL values. This is broadly similar to Fig. 2 in Woodworth 2018, see above.

assumption that despite large deviations at national scale (Penna et al. 2013), the general accuracy of the levelling locally (and to some extent regionally) is of order 20 mm.

A direct comparison of our ODL to ODN adjustments with those tabulated in one-kilometer squares by the OS is problematic, as at some sites ODL elevations were significantly revised (e.g. at Pembroke Dock the 1841 and 1850 bench mark elevations were revised by around 150 mm in the 1860 s, and then revised back again in 1906). Unless bench mark elevations (or in rare cases OS map revisions) are stated in the Admiralty tidal or datum ledgers, this can be a potential source of uncertainty. In the few cases where information is lacking, we assume the latest map revision available at the time was used.

4.3. GIA adjustments

The RSL data is adjusted for the ongoing different post glacial rebound rates around the British Isles (Emery and Aubrey 1985; Peltier and Tushingham 1989; Rennie and Hansom 2011; Whitehouse 2018) using the Peltier ICE-6G_C (VM5a) GIA model data, which includes the effect on measured sea level via both VLM and gravitational effects. The GIA adjustments for each precise site location in mm/yr (column 19 of Table 4 in the appendix) are interpolated from the 0.2 degree gridded GIA model provided by Peltier, and are used to derive a vertical offset adjustment for each site for each year or time period. The intercept or zero offset time value is here defined as the OS levelling date of the local Fundamental Bench Marks (FBM) used in both the SGL and TGL campaigns (column 18 of Table 4), thus all MSL values are referenced to local ODN. To obtain the local Relative Sea Level Rise (RSLR) as it would appear without GIA, the GIA adjustment must be subtracted from the total SLR estimate for each cluster.

Other GIA models are available for the UK, as are CGPS (Continuous Global Positioning System) observation based estimates of recent vertical land motion for a limited number of locations. Those we looked at were similarly effective in reducing the scatter in the derived SLR trends, and we discuss this briefly in section 6.

4.4. Seasonal adjustments

Some of the campaign data observation periods were only a few months, or an average of two weeks for the OS 1859 data. In order to treat these shorter periods of data as representative annual averages, an adjustment for the average seasonal variation (Fig. 8) is necessary, and the associated uncertainty will also be larger than for annual values. Using detrended monthly data from the nearest "core" PSMSL site defined in section 4.7 (with datum offsets adjusted) we estimate the annual and semi-annual sinusoidal components using linear regression to create an average seasonal curve which is then interpolated to daily resolution for each core site. We then take an average of this seasonal signal between the start and end dates of the MSL data, giving a seasonal offset adjustment from the annual mean. This is then subtracted from the mean MSL over the same period. These adjustments can be of the order of 100 mm. The uncertainty for the seasonal adjustment is also derived (see section 4.6). Fig. 8 shows the similarity of the average seasonal monthly MSL variation around the GB coastline, but also shows how the amplitude of this component increases with latitude (Tsimplis and Woodworth 1994; Dangendorf et al. 2013) for the 36 TG locations defined as core sites in section 4.7. The seasonal adjustment is given in column 11 of Table 4 in the appendix.

4.5. Meteorological variability: Extending and testing a barotropic model

Sea level variability due to local meteorological influence between Jan. 1958 and Dec. 2018 is estimated using a barotropic tide and surge model, CS3X, a variant of the UK's main operational tide-surge forecast model (see Hogarth et al. 2020 and references therein). Model outputs are available from the NOC (see overview on https://noc.ac.uk/files/documents/business/model-info-CS3X.pdf). Using a barotropic model has been found to be an effective way of removing sea level variability due to both local winds and atmospheric pressure (Piecuch et al. 2019), leaving a residual which is much more uniform round the UK and attributed to far-field influence (Hogarth et al. 2020).

No high resolution barotropic models currently extend back as far as the early 19th Century, so here we first create an extended sea level air pressure and geostrophic wind data set at each tide measurement site using interpolated 1 degree gridded observations from the recently released 20th Century Reanalysis version 3 (20CRv3) (Slivinski et al. 2019) which extends back to Jan. 1836, combined with interpolated 5 degree gridded data from a reanalysis of historic European air pressure data sets (Luterbacher et al. 2002) prior to 1836. Discontinuities are minimised by using linear regression to develop coefficients to adjust the monthly Luterbacher et al. pressure data for mean level and variability at each site taking advantage of the large temporal overlap with 20CRv3

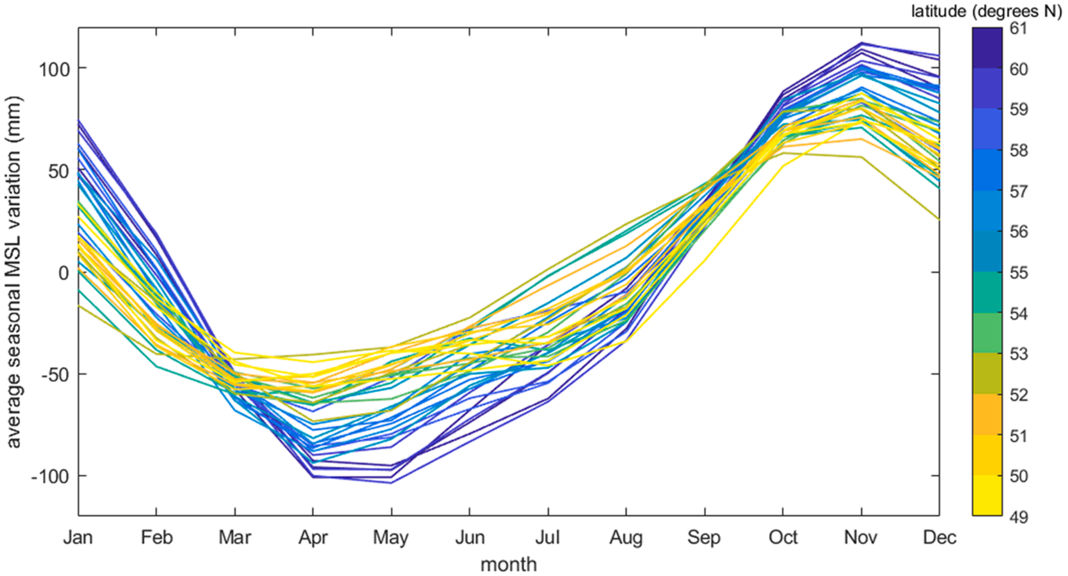


Fig. 8. The average (over length of each record) seasonal variation in MSL for the 37 'core' PSMSL TG sites around the GB coastline, showing the phase relationship and progressive increase in amplitude from South to North.

data. Similarly we extended the geostrophic wind components prior to 1836 using computed pressure difference values from grid points North and South as well as East and West of the site location from the Luterbacher et al data. The new time series at each site are then checked both visually and by comparing with other reanalysis products, including HADSLP2 (Allan and Ansell 2006), noting that a previous version of 20CR, (version 2c) has documented anomalies which lead to poor estimates of global MSLP over the ocean in the mid 19th Century, which can lead to time specific anomalies in Inverse Barometer (IB) adjustment values. These anomalies are not visible in 20CRv3 (or HADSLP2).

Next, the simulated monthly sea level from a version of the CS3X tide and surge model covering Jan. 1958 to Dec. 2018 at each site is linearly regressed using the extended air pressure and wind dataset (with pressure and wind as predictors), to give us a statistical barotropic model covering the period 1813 to 2018. The seasonal cycle is removed from both the barotropic model and the meteorological data to avoid double counting any seasonal variation. We then test this model with deseasonalised tide gauge data, and we demonstrate reduced variability in long MSL records (e.g. Aberdeen). Regression using a tide and surge model rather than the MSL observations ensures that only the locally driven component of variability is being simulated, allowing separation of this from other components present in the MSL record.

For short periods of MSL data (less than 1 month) we use daily meteorological data from 20CRv3 after 1836, or for data prior to 1836, interpolate the adjusted Luterbacher et al. (2002) SLP and geostrophic winds as for the seasonal adjustments above. We check that the differences between mean daily data and interpolated monthly data are low after 1836, and assume this holds before 1836 where we have not yet obtained data at daily resolution. These adjustments are given in the 12th column in Table 4 in the appendix.

4.6. *Uncertainties*

For interpreting the 19th Century values we need an appreciation of the uncertainty in the various adjustments. Table S3 also identifies the sources of uncertainty in each adjustment. Later we will fit weighted trend lines, where the weights are based on these uncertainties. The SLR trends at each site are adjusted with an estimate of GIA, which also has a significant uncertainty, briefly explored in section 6.

For MTL to MSL the uncertainty where predictions are possible is 20 mm, but an unquantifiable uncertainty comes from local shallow water variations in tidal ranges. The 20 mm estimate is thus optimistic. Also, the MSL may increase locally up estuaries and in rivers. In some cases, local distortions will cause outliers which can be identified from the plots. This remains one of the biggest local unadjustable uncertainties.

The uncertainties in the ODL to ODN adjustment are based on the standard deviation within the ODN-ODL differences for individual bench marks at each location. These have an average of 15 mm standard deviation. Outliers exist: the differences for Sunderland and River Tees Entrance show a standard deviation of over 100 mm, possibly attributable to local subsidence.

Within a cluster (see below) transfer of levels from other sites to the core location will introduce uncertainties in the levelling. Although impossible to be sure of the relative components, these transfers were a mix of secondary and tertiary levelling. Harley (1975) gives a confidence limit of:

$$N\sqrt{separation\ in\ km}$$

in mm, where N is 2, 5 and 12.5 for OS Primary, Secondary and Tertiary levelling respectively. We use a pessimistic value of 8.5, which is the mean of Secondary and Tertiary levelling. For example, a 15 km levelling (the average distance between sites) will have a standard error (SE) of 32.9 mm. The greatest distance between sites in a cluster is around 136 km, giving a worst case levelling uncertainty of order 100 mm. Some of the sparsely spread sites are in Scotland where there may be additional error sources due to levelling over dynamic terrain. For Primary Levelling a 1000 km line would have 66 mm confidence limits, whereas we see in Fig. 7 the differences on a National mapping are both systematic and an order of magnitude greater than this (Edge 1959). Also there are unexplained jumps across the Wash, and the Severn Estuary.

For the seasonal adjustments, the variability in storm-prone Winter months is expected to be significantly higher than for Summer months. This can be confirmed by calculating the standard deviation of differences from the mean for each month over many years.

Because many periods in the data set do not extend for a full year (some are as short as two weeks), a related important question is how these standard deviations increase as the length of the data observations is reduced to less than 12 months. The uncertainty as a function of time of year and the length of observation can be represented as a point on a continuous surface, as in Fig. 9. This shows, for Newlyn, the variation in standard deviation (including that due to barotropic variability, i.e. before adjustment) both seasonally and for data spans of one to twelve months of de-trended monthly MSL data. Clearly, a short period of data recorded in the summer months is likely to be more reliable than over the same period in the winter.

We generate a matrix of repeated uncertainty values covering three years (not shown in Fig. 8) to simplify the estimation of adjustment values for dates overlapping year end.

The combined uncertainty for each site, given in column 23 of Table 4, is estimated as the individual uncertainties added in quadrature.

4.7. *Partitioning the coastline into regional clusters*

Table 4 in the appendix summarises the useable data sources, adjustments and uncertainties.

The Ordnance Datums represent a nominally level surface, as determined by large scale levelling exercises. However, levelling errors at the several decimetre level over a national scale (Penna et al. 2013) are too large to allow direct comparison of widely spaced tide gauges. To overcome this in a systematic way we divide, somewhat subjectively, the coastal areas around Great Britain into local clusters, based on regional and expected hydrodynamic proximity. For example, Milford Haven is expected to have different characteristics than the nearby Cardigan Bay region, centred on Fishguard. Some of the clusters may contain more than one PSMSL site with recent data, in this case, for each cluster, the PSMSL site with the maximum number of valid years of recent data,

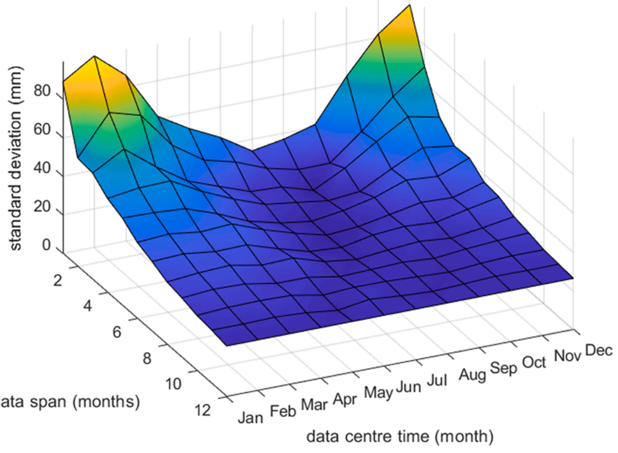


Fig. 9. Plot of estimated seasonal uncertainty for Newlyn showing variation with time of year and period of observations. Similar grids are generated for each core PSMSL site.

levelled to modern revision of ODN, is chosen as the core site. These clusters are shown colour coded in Fig. 10. Within each local cluster it is assumed that:

- OS levelling (ODL and ODN) is accurate, within computed standard errors (see above)
- The mean dynamic sea level is horizontal
- Generally, unless we have information to the contrary, the average MTL-MSL value is constant

5. Results

It is now possible to look at trends separately in the 36 individual clusters, and assess the value of adding the older data to the PSMSL holdings. Plots for all clusters are available in the online supplementary material. Table 4 shows the year and length of data from each source in columns 1 and 2. In section 2.1 we noted that only a handful of the existing PSMSL series contain data from the 19th Century. Three RLR sites have data from prior to 1895, two prior to 1862, and only one has data (Sheerness, 15 station-years) prior to 1858. By utilising the new data sources, almost all 36 clusters now have spans exceeding a century, whilst an extra 1635 station-months or 136.25 equivalent station-year datapoints are added prior to 1900; 833 station-months or 68.7 station-years of these are prior to 1858. These include the important addition of sections of monthly MTL data from the 1830 s to the existing series for the four Naval Dockyards: Sheerness, Portsmouth, Plymouth and Pembroke Dock (Fig. 11).

We will now briefly review the data from these four locations as examples. Each cluster has a letter assigned to it which is listed in the first column of Table 4 in the appendix. For all four Dockyard sites the 1830 s datum information from the Admiralty Datum Ledgers and original documentation was vital. Each plot also has the adjusted and extended monthly MSL for Sheerness plotted in light blue to give a visual reference and indication of the variability we might expect in a typical record at monthly resolution, as well as of the relative differences (offset) between local ODN and local MSL. This helps comparison between the different cluster time series.

5.1. Sheerness, cluster i

Fig. 12 shows the plot of MSL data from Sheerness. Existing observations (PSMSL) at the core station (Sheerness) and two other local PSMSL sites (Southend, 10 km across the Thames Estuary and Tilbury, around 33 km upriver) are shown as smaller open circles. Open

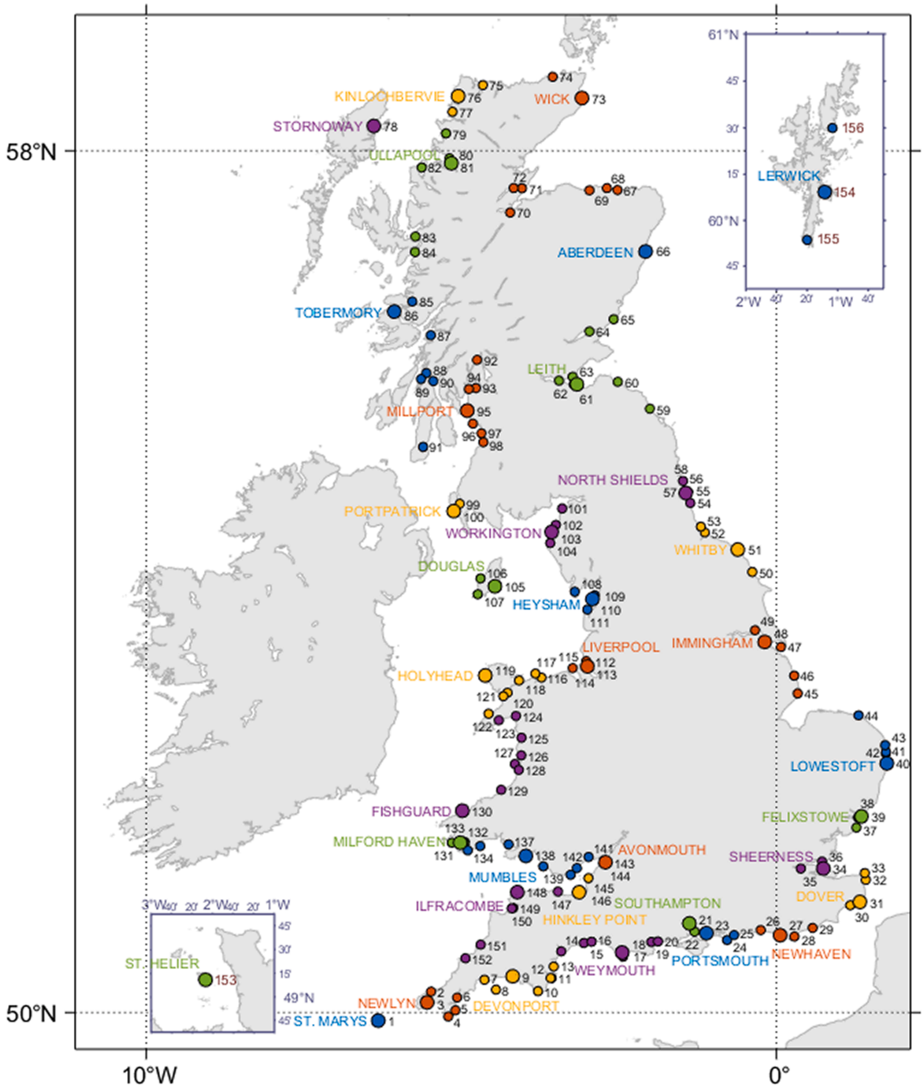


Fig. 10. All sites where data is available, colour coded differently to identify each local cluster. The core PSMSL site for each cluster is shown as a larger marker and is named. In a small number of cases where sea level dynamics (or possibly unaccounted levelling or datum errors) introduce clear sea level offsets (relative to ODN) in geographically close stations, these are treated as separate clusters (e.g. Avonmouth and Southampton).

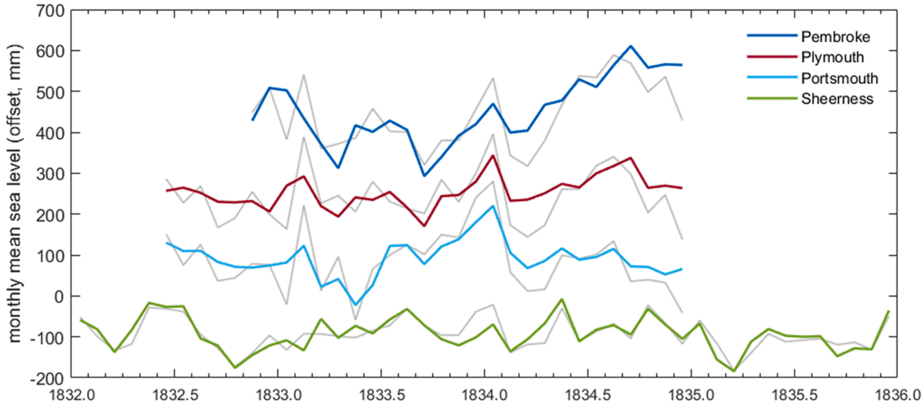


Fig. 11. Estimated monthly MSL at the four Naval Dockyards, the background grey traces are unadjusted for meteorological effects, the coloured bold lines are adjusted. Series are offset to aid visualisation.

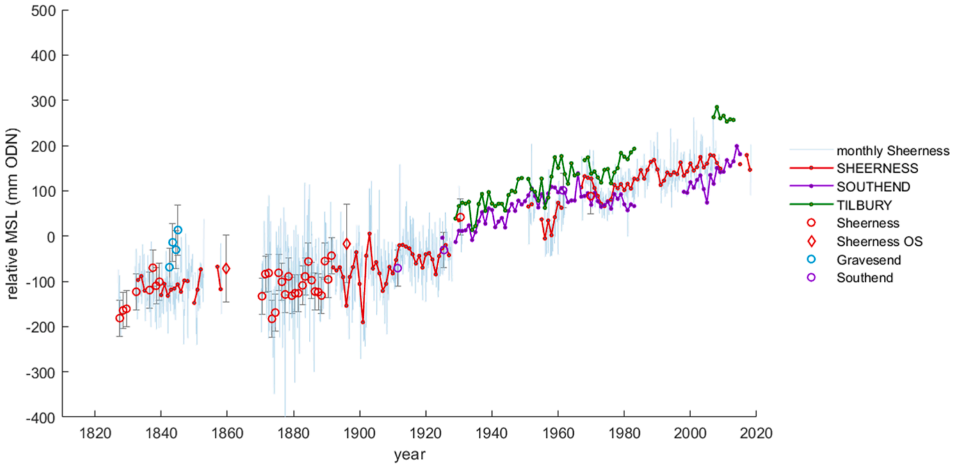


Fig. 12. Plot of data from Sheerness and Southend, resolved into annual MSL values, overlaid on fully adjusted monthly values (light blue) for Sheerness. The filled points (connected by lines if an adjacent value exists) represent existing annual MER (extended and adjusted PSMSL) MSL data. All new data values are represented as larger open circles (or open diamonds for the OS observations) and have total uncertainty estimates shown as grey bars.

diamonds show OS sites from 1859 or 1896. The larger open circles are new data from all sources. All sites are colour coded for location. The grey uncertainty bars for the new data are combined uncertainties from levelling, meteorological, seasonal and MTL to MSL adjustments.

For Sheerness, the PSMSL already holds some data from the 1830 s, as MSL referred to ODN. We recomputed the MTL for 1832 to 1843 from our digitised values, and also checked against the OS (1861) averaged values for 1835 to 1838. The OS 1859 value is aligned with the other points, within the uncertainty levels. The Southend values also agree within the uncertainty limits. Tilbury and Gravesend (across the river) are far enough upriver to suffer potential increased mean water levels due to the slope of the river. We can observe that a) we would need to subtract a centimetric scale offset from the Tilbury MSL data to minimise the mean difference from the Sheerness data, and b) an identical offset subtracted from the Gravesend 1840 s data would result in a similar reduced difference. We will return to this concept in section 5.7. Other nearby tidal observation sites are given in the Tidal Ledger, but are not used: Osea Island is not connected to Ordnance Datum, though local bench marks are defined in the Ledger; Chatham levels in the Ledger are computed by comparison with Sheerness so are not independent. Finally, levels further up the River Thames at Woolwich and London Bridge are excluded because of probable freshwater flow effects (although annual variations are highly correlated). Note that for Sheerness the (MTL-MSL) adjustments took account of nodal variations.

5.2. Portsmouth, cluster f

Fig. 13 is the MSL plot for the cluster around the core site of Portsmouth. The cluster region extends from Portsmouth to Bognor Regis. Values from the offshore Nab Tower were excluded, as there appear to be (typical) levelling issues across bodies of water. Southampton Water, Southampton and Calshot, are grouped elsewhere in the Ledger. The apparent elevation offset difference between Portsmouth and Southampton PSMSL ODN referenced water levels may be due to hydrodynamic factors, or local levelling, or both, but is large enough to justify treating them as separate clusters, a point we will return to later. For Portsmouth, the PSMSL hold monthly RLR MSL from 1961 to 2018, and a year of Metric monthly data from 1930. We resolved the datum offset for the 1930 Metric data, added a small number of additional recorded points from Portsmouth and nearby sites, as well as the important 1830 s adjusted MTL Dockyard values.

5.3. Plymouth, cluster C

Fig. 14 shows the Plymouth cluster and trends. As some of the cluster sites are up creeks we might expect some hydrodynamically elevated values. Without local modern data it is also difficult to estimate MTL to MSL conversion factors. For Devonport, the PSMSL hold monthly MSL from 1961 to 2018. We assume this to be more comparable with the recovered 1830 s dockyard data than that from other nearby sites, which

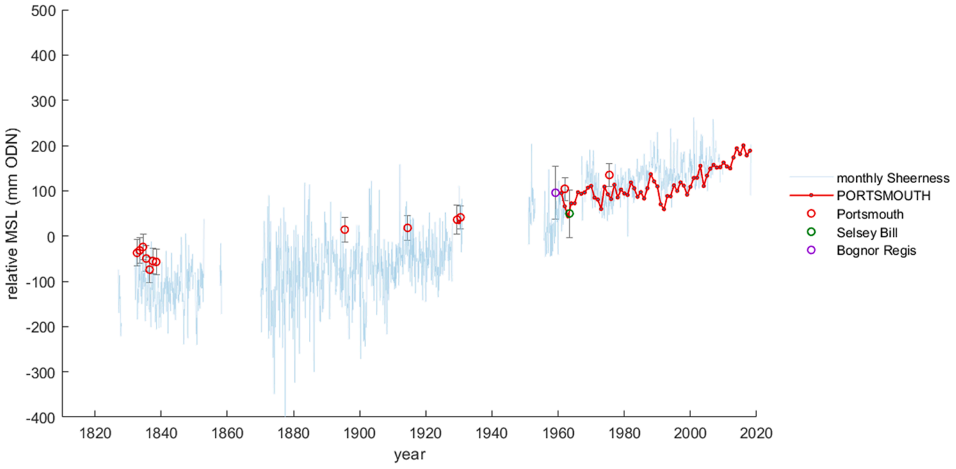


Fig. 13. Plot of Portsmouth data cluster, overlaid on the monthly Sheerness data to help comparisons between cluster time series.

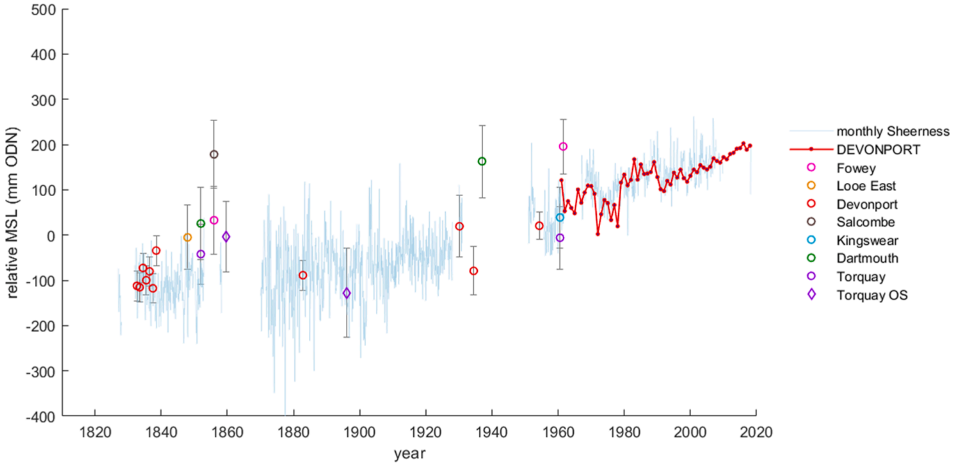


Fig. 14. Plot of Plymouth (Devonport) data cluster, overlaid on the monthly Sheerness data.

is reflected in lower levelling uncertainties. Fortunately, a number of stable bench marks around the Plymouth Devonport Dockyard still exist. The 1833 to 1838 MTLs for Plymouth are recorded in Whewell (1839). The published 1833 and 1834 MTLs agree with our estimates to within 3 mm. Salcombe (1856) appears to be an outlier, whilst Dartmouth and Fowey are consistently high in both 19th and 20th Centuries, suggesting a real modern difference, either from ODN levelling or hydrodynamic differences.

5.4. *Milford Haven, cluster AD*

This is an extensive harbour, with sea level measurements over several years, made at four separate locations from 1832 to 2018 (Fig. 15).

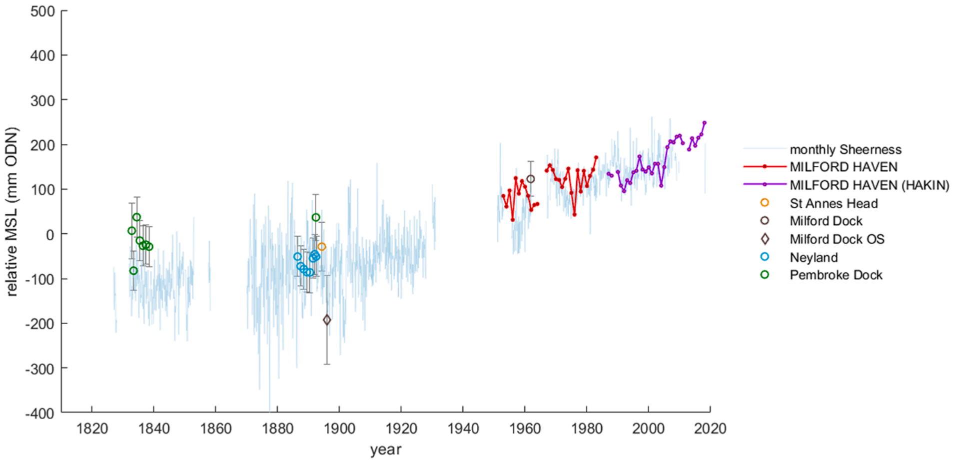


Fig. 15. Plot of data cluster for Milford Haven, overlaid on the monthly Sheerness data.

The Admiralty Dockyard (Pembroke Docks) measurements digitised here extend from November 1832 to December 1834. Another set of observations between 1886 and 1892 (from 1 km across the River Cleddau at Neyland) are given in Thompson (1915) in feet above local ODL at that time. The St Anne's Head level from 1894 fits well, but the larger uncertainties reflect levelling to the remote location. The PSMSL has data from Newton Noyes 1964 to 1980, and Hakin from 1987 to 2018. The Pembroke Dock measurements are not to the same precision as at the other three Dockyards in the 1830 s, as several Low Waters are given to the nearest foot, and sometimes on extreme low tides, the gauge dries out with levels given as "mud". The computed values for MTL omit these Low Waters (and the adjacent High Waters to avoid bias). The majority of the other values are given to the nearest 3 in.. Nevertheless the large number of observations will reduce the uncertainty over each month or year, assuming otherwise random error processes.

There is ambiguity in the ODL and ODN tide gauge bench mark elevations for Pembroke Dock. The 1841 FGL levelling gives an elevation of 14.634 ft above ODL for the Western Camber bench mark, and the stone scale TGZ as 11.864 ft below ODL. Thus the TGZ was 26.498 ft below the bench mark (the Tidal Ledger value gives 26.5 ft). The bench mark elevation was revised to 15.1 ft ODL in the 1860 s, but subsequently does not follow the same pattern of elevation changes as for 40 nearby marks through the 1906 revisions to ODL and later to ODN (all reduced back close to the 1841 values), and in 1953 was levelled at 15.15 ft. It is assumed that the tidal observations published in 1833 were referenced to the zero of the same tide gauge carved in the stone wall of the Camber. Here we assume the ODL to ODN adjustments are represented by the mean of changes in 11 pairs of bench mark elevation differences between 1841 and 1970 (standard deviation of 14 mm) for the data from the 1832 to 1834 tide register, and use the 1860 s levelling for the averaged 1835 to 1838 values reported by the OS. A possible explanation for the rogue elevation is that the joints between granite stonework in the dock wall have expanded, a phenomenon observed elsewhere with similar dock construction methods (Freeman 1903, Talke et al. 2018). Neyland, on the other side of the Cleddau has a mean difference of 82 mm between the revised ODL from the 1860 s (in use when the observations were recorded in the 1880 s) and ODN. The Neyland MTL values are in PSMSL but only as local Metric data. Here we show this data can be fitted into a wider area context. The PSMSL also have later RLR records from Milford Haven (Newton Noyes (red) and Hakin), either side of Milford Dock, these sites already have modern connections to ODN.

5.5. Comparing results from all sites

These 4 and the other 32 cluster sites and new data sources are all listed in Table 4. As well as data from Admiralty sources, we include: all data digitised from 19th and 20th Century scientific publications, data where new datum information from Admiralty Ledgers has allowed PSMSL "metric" data to be incorporated, and values given in historical Civil Engineering documents. In short we have tried to use all possible data where datum information can also be recovered.

Overall the newly assembled digitised data consists of 508 data points, the equivalent of at least 3322 station-months or 277 station-years. A minority of sites record the year of observation, but no dates; if these are assumed to be a typical 1 month minimum, the total increases to 3348 station months. Of these, 456 of the new sites and associated time periods have no equivalent station-month values for any site in the PSMSL, giving more than 2916 unique new station-month values.

We then derive weighted linear and quadratic trends from the time series and estimate standard errors for:

1) PSMSL RLR annual data for each cluster core site over the length of each series.
2) The extended MER annual mean dataset for each cluster core site which has also been optimally adjusted for datum steps (Hogarth et al. 2020), over the length of each MER series.
3) The full historic data set for each cluster including MER data, over the full span of each series.

A small number of data points (8) have been classified as outliers from examination of the cluster plots. These are discussed in section 5.6. These data points are given zero weighting in the final cluster SLR calculations, and are represented by a zero in the final column (column 30) in Table 4.

The results for each cluster including MER data and all new data points, adjusted using GIA values from Peltier ICE-6G_C (VM5a) are tabulated in table S5 in the supplementary material. We assume GIA to be constant over the 200 years, although we note that the modelled rates for GB systematically vary by typically 0.01 mm/yr over periods of 500 years. Fig. 16 summarises the results for SLR illustrating the increased alignment of trend values.

The weighted average linear and acceleration (twice the quadratic coefficient) trends for all clusters (weights based on the inverse of the square of the standard errors in each trend) are summarised in Table 2. The weighted average values differ slightly from the peak pdf values in Fig. 16 due to the relative weighting. The linear and quadratic trends are fitted simultaneously, and the reference year t_0 for the linear trends is 1915 (Hogarth et al. 2020).

Although the impact of adding the new data depends to some extent on the associated uncertainties, which in some cases can appear relatively high, it is likely that this is outweighed by the number of additional points. The reduction in the average standard deviation of SLR from 0.77 mm/yr to 0.41 mm/yr, suggests that adding the new data improves confidence in the estimates of sea level trends. It is also possible that this reduction is related to the increased effective length of the time series (Zervas 2001). Extending the data set by a century is at least as effective as resolving datum errors in the existing dataset in terms of reducing trend differences. For sea level acceleration, (SLA) the improvements are even more marked. This is discussed further in section 6.1. A PDF of computed acceleration values for all cluster sites is given in the supplementary Fig. 2s.

Applying GIA adjustments from Peltier ICE-6G_C (VM5a) only has a minimal effect on the interstation variability or SE, a point noted in Simon et al. (2018) for Northern Europe as a whole. This will be explored further in section 6.

5.6. Outliers

The outliers in the individual cluster plots are explicable in many cases, for example some sites upriver from estuaries such as Cardigan and Appledore have consistently higher MSL values than those of nearby open coast sites with contemporary data. For Liverpool the values for 1868 (and 1872 in the RLR data) are anomalously high, possibly due to the St. Georges floating landing stage (which at that time acted as the float of the tide gauge) grounding on sand which was accumulating under one end of the stage during this period (Le Mesurier 1887). For Barry Island the value for 1861 was recorded before the dock was built, so the dock gauge zero and chart datum must have been applied retrospectively (by comparison). Bunt rejected the first Axmouth value he recorded for 1838, noting it was observed inside the bar at the entrance to the river. Upon investigation the values for Salcombe 1856, Inverness 1837, Portland 1896, and Maryport 1875 also have suspected datum issues and are also treated as outliers. A few other points appear problematic, but without evidence are not treated as outliers here, e.g. the average of the month of observations from Berwick for 1932 appears low. The original datum point for Lerwick (1878) appears relatively high, this may be related to uncertainties in the GIA model (and hence SLR) resulting in an unaccounted vertical offset accumulating over almost a century, but could also be linked to the probable transfer of the

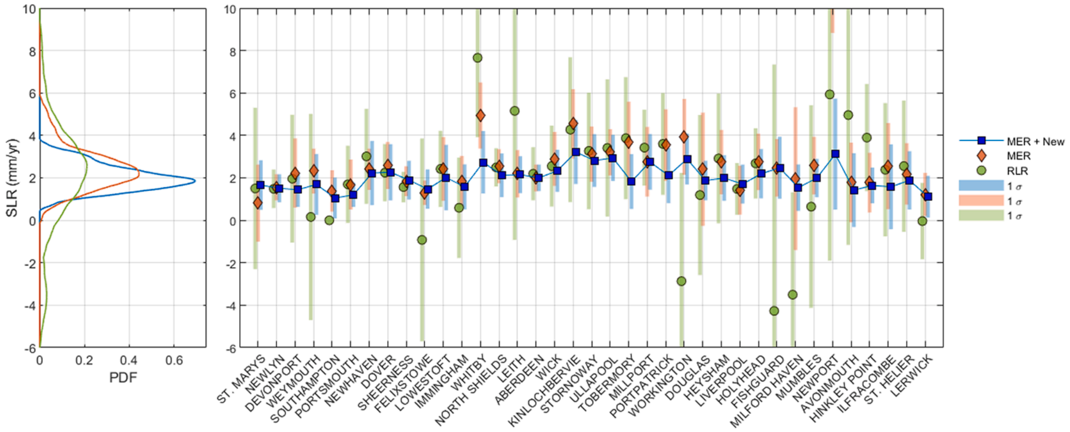


Fig. 16. Right: plot of linear trends (adjusted for GIA) for the primary cluster sites with uncertainties. Green is the original PSMSL RLR data, Red is the extended PSMSL MER data, and blue is the fully extended MER data as well as all new data points. Left: PDF of the same data over the full length of each data series.

Table 2
Weighted average of all 36 cluster SLR trends (adjusted for GIA), and SLA trends with and without weighting. Southampton is not included in the RLR estimates as the PSMSL data is Metric only.

	PSMSL RLR		MER		All data	
	SLR	SD	SLR	SD	SLR	SD
36 clusters (35 for RLR)	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr
Weighted mean inc. GIA	1.94	0.77	2.04	0.62	1.81	0.41
	SLA	SD	SLA	SD	SLA	SD
36 clusters (35 for RLR)	mm/yr^2	mm/yr^2	mm/yr^2	mm/yr^2	mm/yr^2	mm/yr^2
Weighted mean	0.014	0.025	0.016	0.015	0.013	0.008
Unweighted	0.173	0.735	0.020	0.072	0.014	0.010

datum from Heogan across Bressay Sound at an early date.

The small number of suspect data points (see Fig. 19) are given zero weighting in the analysis of the overall trends (Fig. 16 and Table 2). The final cluster trends are our best estimates of the average SLR at each location, again relative to local bench marks. The weighted mean SLR of all clusters is 1.81 mm/year with a weighted standard deviation of 0.41 mm/year.

Obviously we are deriving trends from differing record lengths, and estimating trends from sparse irregularly sampled data is problematic. However the extension of time series at all sites, even when numbers of additional data points are small, reduces the spread of trend values. The mean SLR is also reduced as the average series centre time is moved back in time. This would be expected if there was a common century scale acceleration component underlying all time series and the series were lengthened.

5.7. Changes in MSL over 200 years around the British Isles: Aggregating cluster results

We then estimate the vertical ODN offsets between different clusters by simultaneously solving for mean vertical offset differences between the corrected and adjusted cluster MER MSL records using least squares (accounting for gaps and different start/end times). For a number of sites where more than one MER series is included in a cluster we also estimated the MSL referenced ODN offsets for these secondary sites. The difference between core and secondary site offsets is usually small, (cm scale; Fig. 17). The next step was to apply these offset values to all newly recovered data within each cluster based on distance from the nearest MER site. Where a new data point site is closer to a secondary MER site than the core MER site, the secondary offset value was applied to the nearest new data points in preference. We make exceptions for data from the PSMSL sites identified in Hogarth (2020) as suspect due to possible subsidence (Newport and the Whitby) which would otherwise bias the mean offset difference. This refinement (introducing an additional 22

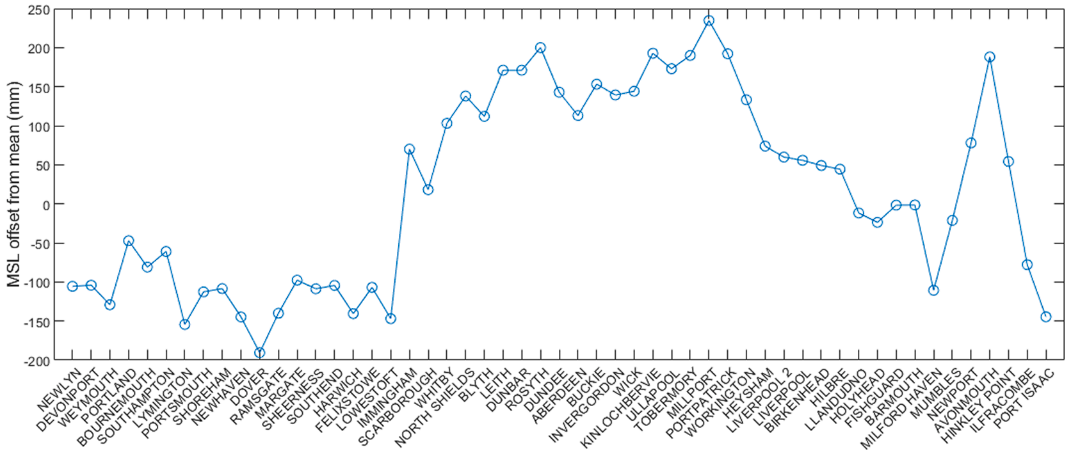


Fig. 17. Plot of offsets applied to all MER cluster and secondary sites used, determined from least squares. These include any ODN levelling errors, and site to site differences show that most adjacent sites have similar ODN related MSL levels, with exceptions across the Wash and for the Severn estuary. Island sites are not represented here.

PSMSL/MER sites to the 36 core cluster sites which were originally selected) further reduced scatter in the recovered data results, and also accounted for MER sites which appeared to have larger time-averaged MSL differences in periods of temporal overlap than might be expected from the short levelling distance between them (e.g. Shoreham and Newhaven). The final offset values are shown in Fig. 17. The PSMSL id. number of the reference site used to derive the offset value for each new site and the distance between them is listed in columns 15 and 16 of Table 4 respectively, whilst the offsets are listed in column 25.

The aim is to reduce the data in each cluster to a common MSL related datum, assuming any site to site MSL datum differences are due to a) long range levelling errors (Penna et al. 2013) and b) any constant (in time) dynamic topography differences between sites, which may be real, but prevent distant sites from being combined into a single time series.

Fig. 18 shows the effect of applying these offsets to the MER ODN referenced annual MSL data (red) with the site (cluster) offsets from the MER common mode subtracted (blue). The MER data has meteorological variability minimised using the methodology described in section 4.5 and estimated datum steps removed as in Hogarth (2020). The small number of outliers in individual time series are dealt with in a similar way to the PSMSL RLR data. The spread of data values has been reduced to the point that the common mode signal and variability are now clearly visible over most of the 20th Century.

We now apply the appropriate cluster offsets to the newly assimilated data points in each cluster. These offsets, derived purely from comparing the MER data series, are the only connection between the MER data and the new independent data points.

Compared with pre-adjusted data, this again greatly reduces the spread of MSL values between clusters (Fig. 19), the standard error of derived linear trend reduces from 0.138 to 0.081 mm/year. This would be expected if local variability due to meteorological effects has been accounted for and any remaining dynamic interannual or longer period variability due to far ocean effects is common to all sites.

We can then independently estimate (using new data only) how the average MSL for the British Isles has varied over a 200 year period, for example here by using a five year running weighted average (red broken trace in Fig. 19).

Comparing with Fig. 18, the long-term MSL variation looks similar, but the density of new early data is greatly increased. The gap between the 1980 s and 2000 s is because IHO data points for this period are annual or multi-year MSL averages extracted from the same tide gauge network which contributes to the annual GB PSMSL records (i.e. they are not independent).

The MER data (blue) is again shown in Fig. 20, overlaid onto the new points (red). The annual common mode using the MER data is shown here as a solid blue line, whilst the red broken line is the independent 5-year running average for the new data alone. The only use of MER data in constructing the latter line is to estimate the site-dependent time-mean vertical offsets for each cluster, as shown in Fig. 17. For each cluster, the difference between early and later new data is independent of the PSMSL data.

All existing and new data points have now been systematically reduced as far as possible to a single datum level. This allows an annual weighted average sea level curve and uncertainties to be estimated for Great Britain over the entire period using all available data. The result is shown in Fig. 21, where uncertainties in grey are error estimates for years in which there are multiple sites contributing (weighted by the inverse of the estimated errors for each contributing site). Uncertainties in red are the estimated errors accounting for levelling, MTL/MSL and seasonal adjustments where only a single station has contributed.

We now investigate the changes in SLR using several methods. We derive SLR and second order SLA trends for the newly combined annual time series, accounting for the possible effect of coloured (temporally correlated) noise in the MSL signal by using a MATLAB version of the Create and Analyse Time Series (CATS) software (Williams 2008). We compare 19th and 20th Century weighted linear trends, and also develop two stick models and a final three stick model based on minimising the difference between model and observations using weighted least squares.

The linear trend (adjusted for GIA) of the time series of weighted annual means is 1.63 mm/year (standard error 0.14 mm/year) based on the centre year of the series. The estimated acceleration over the whole period is 0.010 mm/yr^2 with a standard error of 0.003 mm/yr^2. The linear trend has additional uncertainties associated with the selection of GIA model, discussed in section 6.

This estimate of SLA is consistent with previous long term estimates for the British Isles using the PSMSL dataset; for example a SLA of 0.0110 ± 0.0056 mm/year^2 was reported in Woodworth et al. (2009a,b) (NB Woodworth reports the quadratic coefficient, which is half the acceleration). Fig. 22 shows that while the addition of a few station-years to the late 20th Century dataset is likely to have minimal impact on the aggregated results, we might expect improvements due to the addition of the large number of data points in the first half of the 19th Century. This can be explored by arbitrarily limiting the analysis to the period before 1900.

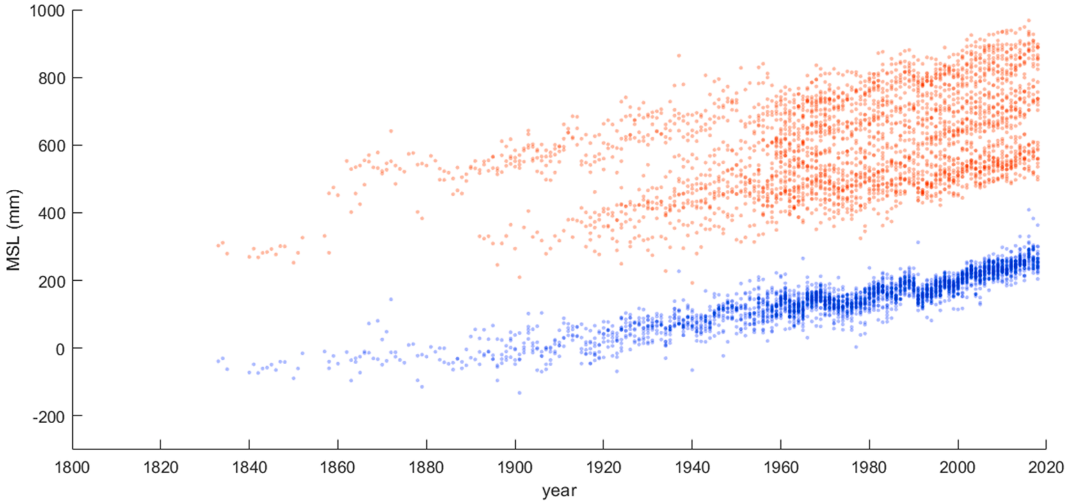


Fig. 18. Plot of all MER annual data, red: top, reduced to ODN with a centre date of the levelling of the OS fundamental bench marks. Blue: bottom, the same data reduced to a common MSL datum by subtracting the offsets from the common mode (or cluster offsets) as above. The top plot is offset by 400 mm for clarity. Optical density is used to indicate data point overlap.

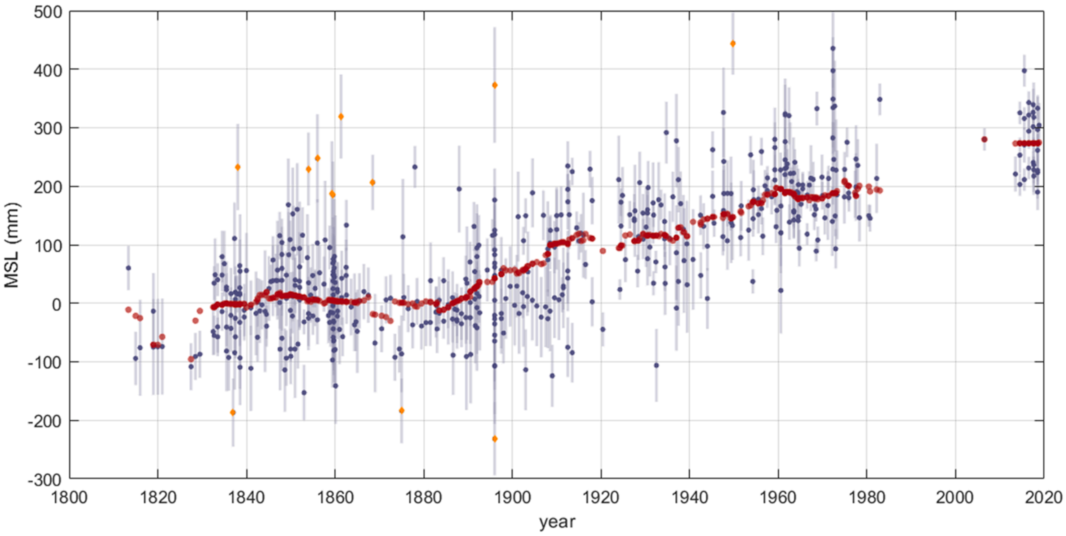


Fig. 19. Plot showing only the new data points (blue, with outliers as orange diamonds) and uncertainty bars (grey), once offsets independently derived from the nearest MER sites have been applied. The small number of outliers do not contribute to the five year running weighted mean, shown in red.

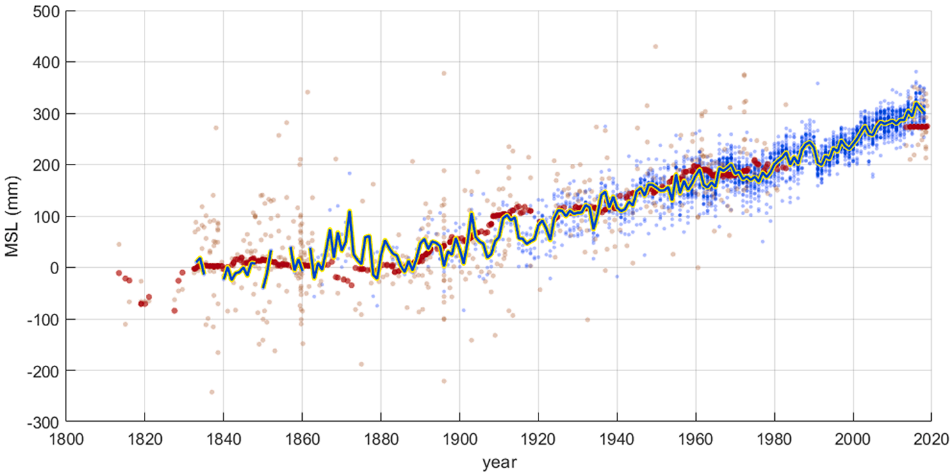


Fig. 20. The MER data (blue) and new recovered data (red) plotted with the same cluster offsets applied. The red trend line is the 5 year running mean of the new data. The blue line is the common mode derived from the extended annual PSMSL data only.

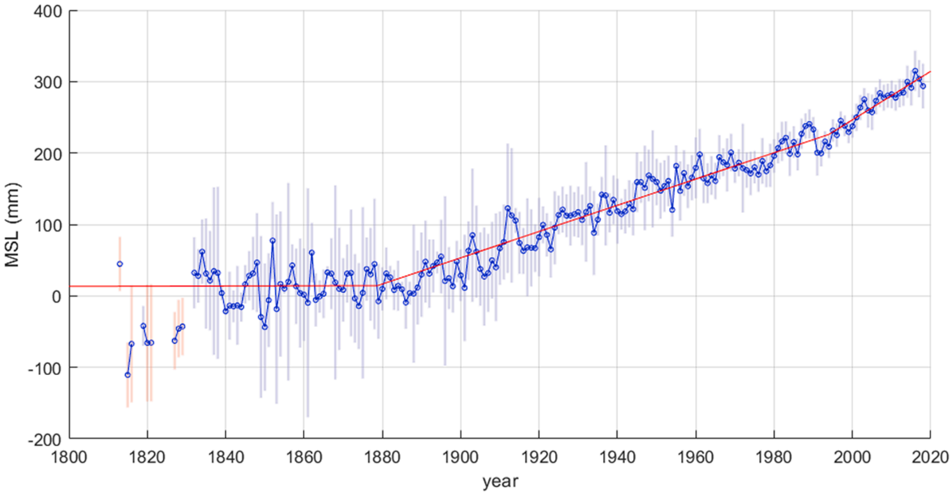


Fig. 21. Common mode (weighted annual average) of all data points, with uncertainties (blue open circles with lines connecting adjacent years). The grey uncertainty bars represent weighted standard deviation, the red uncertainty bars represent the combined uncertainties for an annual value at a single site. The segmented red line is an optimum piecewise linear trend fit (three stick model).

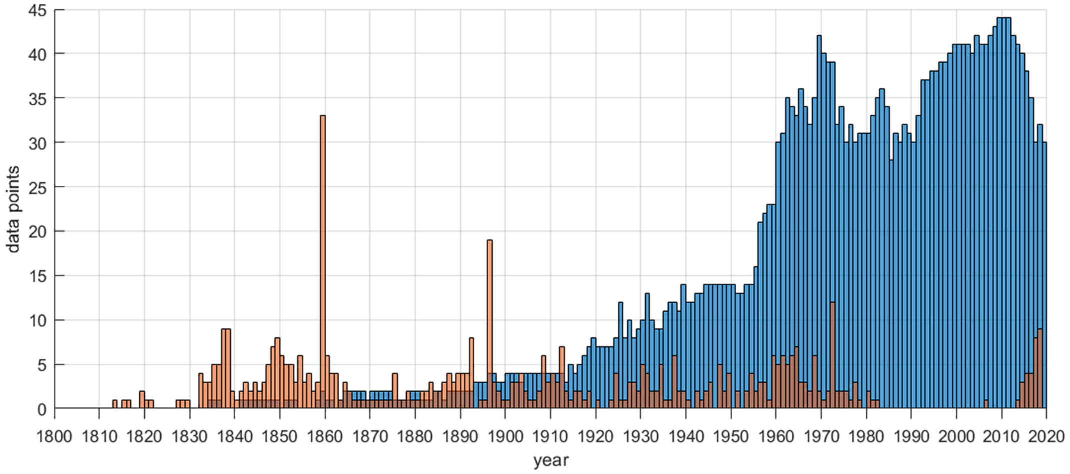


Fig. 22. Histogram of number of annual PSMSL data points (blue) and new data points (red) showing the increased number of new observations prior to 1900.

We derived weighted least squares estimates of linear trend of the weighted annual means for the 19th Century for:

i. the MER dataset, giving 0.47 mm/yr with a standard error of 0.19 mm/yr using 130 station-years from a limited number of sites.
ii. the new data set, giving an independent value of 0.10 mm/yr with a standard error of 0.19 mm/yr using 268 data points and many more sites.
iii. All data combined, giving 0.24 mm/yr with a standard error of 0.12 mm/yr.

We similarly derived trends for the 20th Century (from 1900 including the early 21st, up to 2018) for:

i. the MER dataset, giving 2.15 mm/yr with a standard error of 0.02 mm/yr using a large number of station years and sites.
ii. the new data set, giving an independent value of 1.86 mm/yr with a standard error of 0.11 mm/yr using a much lower number of station years than the MER dataset (this is likely to be biased low due to the data gap between the early 1980 s and the mid 2010 s).
iii. All data combined, giving 2.12 mm/yr with a standard error of 0.02 mm/yr.

As the MER or RLR dataset has only one site (Sheerness) pre-1858, there is a possibility of bias in the trend if any GIA or datum related offsets exist between Sheerness and the other RLR sites towards the end of the 19th Century. Importantly, the greater data density and spatial diversity over a longer period of the 19th Century in the new independent dataset gives increased confidence in the conclusion of Woodworth et al. (2009a,b) that for the UK the MSL trend over the 19th Century is significantly lower than over the 20th.

We then explored the timing of a possible change in slope between the 19th and 20th Century SLR using a two stick model, varying the breakpoint for best weighted least squares fit (over all dates). This gave:

i. For the MER dataset, a break point of 1896 (standard error 4 years) with an estimated trend up to this date of 0.39 mm/yr (standard error 0.24 mm/yr), and post break point trend of 2.15 mm/yr (standard error 0.02 mm/yr).
ii. For the new data set, a break point of 1889 (standard error 7.4 years) with an estimated trend up to this date of 0.16 mm/yr (standard error 0.32 mm/yr), and then post break point trend of 2.16 mm/yr (standard error 0.13 mm/yr).
iii. For all of the data combined, a break point of 1888 (standard error 2.9 years) with an estimated trend up to this date of −0.04 mm/yr (standard error 0.17 mm/yr), and then after this date a trend of 2.12 mm/yr (standard error 0.02 mm/yr).

The timing of this break point and relative trend values appear consistent in the independent datasets. This adds further weight to findings of an SLR increase in the late 19th Century in other long Northern European tide gauge records (Woodworth 1990, Wahl et al. 2013). We also note that if a three stick model is used for the MER or combined MER and new data (Fig. 21), then the best additional fit breakpoint is in 1994, with an increase in SLR from around 2 mm/yr over the preceding century to 3.4 mm/yr from 1994 to 2018. Although these models (and any long term trend) are oversimplifications of the real long term variability, a three stick model may be more appropriate in this case as, on varying the breakpoint when fitting a two stick model, we find two distinct minima in the weighted variance of residuals, centred around the 1880 s and 1990 s.

6. Discussion

6.1. Nonlinearities and acceleration

Whilst there will be uncertainties associated with the assumption that there is an approximate single common mode for the sea level rise rate for Great Britain, this common mode has been shown to be robust since at least 1958. The various causes of datum shifts observed in the modern mechanical tide gauge period (Hogarth et al. 2020) are also likely to affect the earlier fixed gauge observation period. This likelihood is increased for campaign data by the discontinuous nature of observations from temporary gauges (including set up and levelling), contributing to the higher spread in the newly assimilated MSL values. These effects are reduced here by using as many observations as possible in the aggregated results. Deriving trends for individual clusters also requires caution due to the sparse temporal sampling (and lower weighting) of early data compared with more recent data. Although the greater than century scale spans can reduce the impact of any given vertical uncertainties in widely spaced samples, this assumes that large unexpected excursions do not occur in the unsampled sections of time series. Whilst the aggregation of data from multiple sites again helps overcome this and should allow construction of a more representative overall time series, the greater spans will proportionally increase the impact of uncertainties in trend (for example those associated with GIA) on the estimated MSL values.

Although we have computed linear trends for the aggregated RLR and MER data for comparative purposes, Fig. 20 indicates that a linear trend at two century scale is not a representative model for sea level variation around the British Isles. There is a marked increase in slope over the recording period. We can test this by fitting a quadratic curve to the data, allowing quantification and comparison with results of previous studies. Although this can be problematic with sparse data, when a weighted second order trend is fitted to each of the individual cluster plots, 33 out of 36 show an increase in the rate of SLR between the start and end of the observation period, with a mean acceleration of 0.014 ± 0.005 mm/yr^2, similar to that derived for the handful of long UK PSMSL series (Woodworth 1999, Woodworth et al. 2009a). Importantly, when the new data is also reduced to a common datum and aggregated into weighted annual mean values, changes in SLR including acceleration are evident, allowing a second order trend to be independently derived which is almost identical to that from the MER series. This long term acceleration in sea level is not steady, but appears to show two decadal periods of increase in the rate of SLR, one in the early 20th Century, and a more sustained period from the late 20th Century to now. It is remarkable that this is also seen in global analyses (Woodworth et al. 2011, Dangendorf et al. 2019). These are closely connected to the resultant break point times and segment trends of the simple three stick model shown in Fig. 20. The relatively high acceleration values found when the time period analysed is limited to 1958 onwards (Hogarth et al. 2020) can be explained by the slowdown in the 1960 s and rise in the recent period, which is also evident in global studies (Woodworth et al. 2009b, Frederikse et al. 2020). Looking at shorter temporal scales, for the aggregated RLR and MER data (Fig. 18), even after adjustment for localised meteorological effects, there are pronounced common mode interannual variations e.g. in 1990/91 (Frederikse et al., 2016). In previous work these interannual variations have been strongly linked to variability in integrated alongshore winds along the boundary of the Eastern Atlantic from the late 19th Century onwards (Calafat et al., 2012; 2013; Roberts et al. 2016, Hermans et al. 2020), and the sea level signal (once local meteorological effects have been adjusted for) has similarly been shown to be highly correlated along the shelf boundary from North Africa all the way to the Arctic Ocean (Hogarth et al. 2020) over at least the last 25 years. Fig. 11 in Calafat et al. (2012) implies that choice of start and end points combined with the decimetre scale interannual perturbations caused by alongshore wind variations will affect short term (decadal scale) coastal sea level trend analyses, and is likely to affect estimates of the timing of apparent change points in SLR along the entire North Eastern Atlantic boundary. Volcanic forcing may also play a part (Gregory et al. 2013), the change points following shortly after the major Krakatoa (Gleckler et al. 2006) and Pinatubo (Nerem et al. 2018) eruptions. Whilst the common mode signals for both the MER and independent new dataset both have least squares best fit change points around 1890, caution is required when assessing any higher temporal resolution variation in the averaged signals, as the improved 19th Century data density (Fig. 22) and confidence in datum levels are still much lower than for the late 20th Century data. It is difficult to increase confidence in the interannual variation apparent in the early data by comparison with independent regional tide gauge time series because there are very few sites with continuous data from this period. A comparison of our annual GB common mode with annual PSMSL data for Brest (the latter adjusted for atmospheric pressure and geostrophic winds as described in section 4.5, and then both data series detrended) which contains MSL data from 1807 but has a ten year gap between the end of 1835 and the start of 1846, shows higher correlation (0.58) than for any of the individual GB sites correlated with the GB common mode, and also shows slightly higher correlation than that of Brest with the averaged MER dataset. However, the correlation degrades before 1835, implying there may be issues with one or both datasets over this period. We can similarly compare with the long historical series from Amsterdam (van Veen 1945, Spencer et al. 1988) by creating a composite of the Amsterdam annual values with PSMSL data from Den Helder for years after 1925 (Fig. 23)

CATS (Williams 2008) derived estimates of SLR and SLA (accounting for coloured noise) for time series of weighted annual means of the newly assimilated data, existing RLR, extended MER and MER plus the new data are summarised in Table 3. The mid-range reference year t_0 (about which the estimated linear trend is centred) is 1915. The standard error values are approximately two to three times larger than those derived from an analysis assuming a white noise model, whilst the effect on trend values is minimal. All trends and accelerations agree to within one standard error, and accelerations are clearly demonstrated at over 2.4 standard errors (greater than99% significance level if Gaussian). Using the MER dataset (PSMSL improved and extended using newly-discovered datum information) reduces the errors on the PSMSL estimates, and the new data independently confirm the trend and acceleration seen in these datasets with their limited 19th century sources, while greatly increasing confidence in the 19th century data. The linear

Table 3
SLR and SLA estimates for the last two centuries derived from time series of annual averages of MSL at all valid sites for: only new data sources, PSMSL RLR data, MER data and finally, the MER data combined with the new data.

	SLR (mm/yr)	SE (mm/yr)	SLA (mm/yr^2)	SE(mm/yr^2)
Newly recovered data	1.62	0.11	0.010	0.004
PSMSL annual RLR	1.56	0.14	0.012	0.005
MER annual	1.67	0.08	0.013	0.003
All data combined	1.62	0.09	0.010	0.003

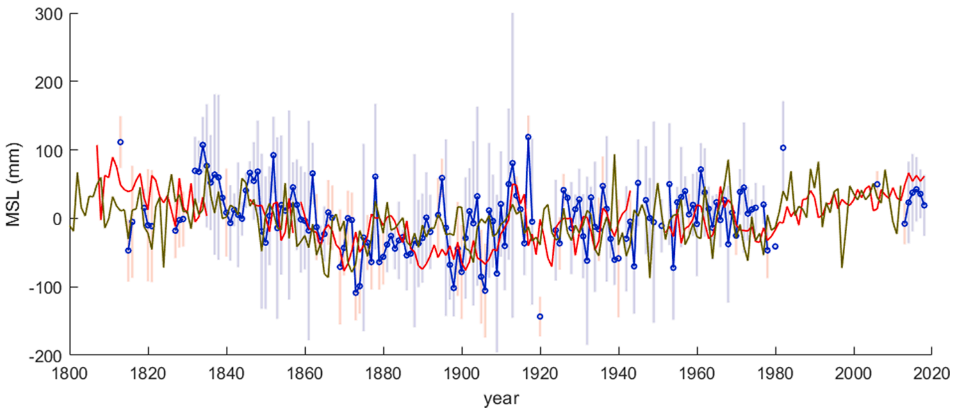


Fig. 23. Weighted annual means of the new MSL data only (blue with open circle markers) and annual mean values for Brest (red) and Amsterdam/Den Helder composite (green) adjusted for inverse barometer and geostrophic wind (all series linearly detrended). Uncertainty bars for new data only are shown, with colours as in Fig. 21.

trends are lower than the respective averages of the individual SLR cluster values in Fig. 16 as the new aggregated times series are now essentially gap free and include all available site-years, effectively increasing the weight of the 19th Century data. This reinforces the conclusion from section 5.7 that a linear fit is a poor model for the variation of sea level over the past two centuries. The change in SLR slope between the 19th and 20th Centuries (Gehrels and Woodworth 2013) means that a linear trend will tend to reduce as the time period of analysis is extended back into the 19th Century, so such overall trends should be interpreted cautiously (and with awareness of the GIA model used).

6.2. *Crustal movement*

The differences between various GIA models and reference frames has been identified as a major source of uncertainty in regional SLR estimates (Wöppelmann and Marcos 2016, Santamaría-Gómez et al. 2017, Simon and Riva 2020). The longer time series presented in this paper offer further scope for investigation of the GIA component (Valentin 1953), which we have assumed here to be well modelled by the Peltier ICE-6G_C (VM5a) (Peltier et al. 2015; Argus et al. 2014). We see an apparent increase in rates of SLR at higher latitudes after modelled GIA effects have been removed (Fig. 16), opposite to that discussed in Woodworth (2018). This is most likely explained by the differences between the Peltier ICE-6G_C (VM5a) and Bradley GIA models (Bradley et al. 2011, Shennan et al. 2012, 2018) used. We briefly investigated this, finding that using the Bradley model did indeed reduce the link of SLR to latitude, and also gave average SLR figures on average 0.37 mm/yr lower than those reported here using the same MSL data. As expected this made the estimated SLR results more comparable with other UK MSL studies using similar GIA models (Woodworth et al., 2009a,b, Haigh et al. 2009) but this does not alter the main conclusions of this paper about acceleration or relative change in SLR since the 19th Century, which confirm and refine those of previous studies. As any real GIA errors will result in apparent site to site offsets which vary linearly with time, this leads to the suggestion of simultaneously solving for a first order (linear trend) adjustment as well as offset in our array based common mode least squares method.

It is also likely that current mass loss in Greenland is contributing to far field vertical land movement (VLM) in the UK through the elastic VLM response (Kleinherenbrink et al. 2018, Frederikse 2019, Ludwigsen et al 2020). This would contribute to any differences between modelled GIA and CGPS observation derived VLM. We defer investigation of these factors to future work.

7. Conclusions and future work

Including all the extra historical data summarised in Table 4 substantially improves confidence in the local trend estimates. The weighted standard deviation of the cluster trends is reduced on average from 0.103 mm/year to 0.031 mm/year. The aggregated data is extended and densified in the early 19th Century, and increases confidence that the single PSMSL GB record which currently extends into the first half of the 19th Century (Sheerness) is broadly representative of the sea level around the entire GB coast, as well as following similar patterns as other long European records on the Channel and North Sea coasts.

Our best estimate of a single Great Britain MSL rise, after adjusting for vertical land movement is 1.62 mm/year, with a standard error of 0.10 mm/year derived using a mid-range reference year t_0 of 1915 (Hogarth et al. 2020). The estimated acceleration over the whole period is 0.010 mm/yr^2 with a standard error of 0.003 mm/yr^2. These estimates account for the presence of coloured noise, and are likely to be more realistic than using a white noise model, which gives estimates of uncertainties 2 to 3 times lower.

The addition of the newly digitised 1830 s Admiralty data for the four Dockyards alone is a major improvement to the UK sea level data set. The new data has been tested against the few earlier publications of the data (Sheerness and Plymouth) and found closely compatible. The connections at ODL and hence ODN would not have been possible without access to the Admiralty Datum Ledgers.

Although of more variable quality, the Tidal Ledger data has also proved extremely valuable. The 1859 OS 15-day sets of data have in general also fitted the cluster trends.

There is, nevertheless, scatter in the final trends as shown in Fig. 16. The structure of our analysis allows us to identify ways in which it would be viable to investigate this scatter in detail.

- The conversion from MTL to MSL needs more local sea level measurements and tidal predictions, though in many cases the exact place is not known, and there may have been changes of bathymetry and therefore harmonic constituents of the tidal waveform and thus MTL. These bathymetry changes are often recorded in civil engineering and historical port authority documents, giving scope for model based studies.
- The adjustments for seasonal changes, and for weather effects (wind and air pressures) could be further refined using improved modelling of the sea level changes in the 19th Century. A limitation is that precise observation times for many of the early MSL data are not specified in the information available. Further work could explore the use of historical observational data from individual sites near the tide gauge locations, which is recorded in the tidal ledgers in some cases. Some of these are already assimilated into the 20CRv3 reanalysis.
- Better adjustments for vertical land movements. Longer term measurements using CGPS over more of the UK will in time allow refinement of estimates of GIA and any modern VLM (Hamlington et al. 2016). Although not the focus of this paper we looked at existing CGPS estimates for sparse sites in the UK and confirmed a similar pattern of scatter in trends to using GIA models. The influence of modern mass redistribution will produce VLM and gravity changes which are not linear in time (Frederikse et al. 2019), and is likely to account for some residual signal.
- It is likely, given the detailed work on bench mark comparisons herein, that only modest improvement can be made in this area. However, for some sites where ODL was substantially revised the ODL version used for datum control could be confirmed with more historical metadata. In addition, where doubt exists as to the stability of old tide gauge bench marks, or vertical distance between the bench mark and a fixed tide gauge zero (e.g. on tide scales carved into dock walls), these could be checked by standard levelling or measurement.

This paper shows the importance of rescuing some of the historical sea level data for Great Britain. More generally, there are likely to be similar old tidal records and metadata in other National archives (Caldwell 2012, Hogarth 2014, Wöppelmann et al. 2014, Bradshaw et al. 2015). The UK Admiralty archives alone hold a large amount of well organised information, including data for many non-UK ports assimilated over a long history of global charting and tidal prediction. A program of tide gauge data recovery (similar to that already underway for atmospheric observations) would prove invaluable. Extending the global sea level observational database will allow us to better quantify how sea level has changed and further improve our understanding of the causes (Marcos et al. 2017, Frederikse et al. 2020).

Data Availability

Table 4 containing the new site MSL data and all adjustments is supplied in document form as well as .csv spreadsheet format in the electronic supplementary material. Additional supplementary material is available which includes Tables S1 to S5 and a .pdf document containing plots of MSL data for all 36 cluster sites following the format of Figs. 12 to 15. Also included are .csv spreadsheet files containing the updated extended MER dataset for all UK sites referenced to local ODN as well as the final common mode of GB time series (weighted annual averages of all GB data) derived in this paper. Page images of the majority of the Admiralty Tidal Ledger are contained in supplement 2.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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All code used in this research was developed using MATLAB® release 2020a. The weighted running mean (Fig. 19) MATLAB code is adapted from Greene (2020).

MATLAB® is a registered trademark of The MathWorks, Inc., Natick, Massachusetts, United States.

Appendix A

Table 4, summarising the useable data sources, adjustments and uncertainties. The blue text is used to indicate observations from the OS FGL campaign of 1859/1860, described in section 3.3. The data is arranged in rows, grouped by main cluster name indexed alphabetically, and by sea level measurement site location. Column 1 and 2 for each site gives the year of observation, and the number of months over which observations were made. Column 3 gives the original average MTL or MSL value relative to the local tide gauge or Chart Datum (CD) used, in the original units of feet (or mm for modern measurements, 1 ft = 304.8 mm is used here). Column 4 gives the TGZ to the same datum in the original units, and column 5 and 6 gives either MTL or MSL (whichever is given) relative to local Ordnance Datum (OD), converted to mm. Column 7 gives an estimated elevation offset between MTL and MSL (mm). Column 8 gives the local bench mark derived datum elevation offset from original OD to the latest ODN revision (3rd). Column 9 gives measured MSL relative to this revised local ODN (mm). Column 10 gives an estimated average seasonal adjustment for observations of less than a year (mm), column 11 gives an estimate of the average modelled meteorological sea level adjustment required (mm) over the period of observation. Column 12, in red, gives the MSL value relative to ODN for that site over the same time period, adjusted for MTL to MSL, seasonal and meteorological factors. Column 13 and 14 give the Latitude and Longitude of the site (decimal degrees N, and E from Greenwich, respectively). Column 15 gives the PSMSL site ID number of the cluster reference PSMSL time series used as the basis for ODN offset adjustments for that site (NB, for some clusters more than one PSMSL site is used, as discussed in the text). Column 16 is the linear distance (km) between the PSMSL reference site and the observation site. Column 17 is the approximate year that the ODN fundamental bench mark levelling, as used for ODN(3), was carried out (this is the pivot year for GIA related MSL trend adjustments). Column 18 gives the modelled GIA trend, adjusted for the geoid, and column 19 gives the vertical offset due to GIA relative to levelled ODN in the pivot year (estimated from the vertical land motion over the difference in years between MSL observation and ODN levelling). Column 20 gives the levelling uncertainty (assumed related to distance between PSMSL reference site and observation site). Column 21 gives an estimate of the MTL to MSL conversion uncertainty, and column 22 gives the estimated uncertainty due to seasonal adjustment. Column 23 gives the combined uncertainty (the previous three uncertainties added in quadrature). Column 24 gives an initial estimate of the cluster site SLR. Column 25 gives the overall least squares estimated offset between each site and the mean ODN relative value (effectively, the mean vertical difference between site sea level curves and the common mode GB sea level curve, due to all contributing factors). Column 26 is simply a row index. Column 27 and 28 give either the original start and end dates of observation, or the centre date and duration of observations, to daily resolution (both formats were used by the Admiralty), where given. Column 29 gives a brief reference for the source of data, the Tidal Ledger is from the Admiralty archives, IHB is the International Hydrographic Bureau sheets, Tidal Analysis is the PSMSL tidal analysis (original calculation sheet document sometimes used by IHB and the Admiralty in late 20th Century). Column 30 gives a weighting value of zero for the small number of data points identified as outliers.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pocean.2021.102521.

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