Report by the Permanent Service for Mean Sea Level (PSMSL) for the Period 2015-2019 to the XXVII General Assembly of the IUGG, Montreal, Canada, July 2019

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Overview

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long-term sea level change information from tide gauges and also provides a wider Service to the sea level community. The PSMSL continues to be responsible for the collection, publication, analysis and interpretation of sea level data. PSMSL is part of the National Oceanography Centre (NOC), Liverpool, with funding provided by the UK Natural Environment Research Council (a component of UK Research and Innovation). PSMSL operates under the auspices of the International Science Council (ISC) and in 2015 was accredited as a regular member of its World Data System. In 2018, PSMSL celebrated its 85th anniversary by hosting an international meeting. The "Sea Level Futures" Conference, attended by over 100 delegates from 65 international organisations, was dedicated to examining the current state-of-knowledge and future of sea level research.

The primary aim of the PSMSL is provision of the global data bank for long-term sea level information from tide gauges. PSMSL has continued to increase its efforts in this regard and over the last four years almost 10000 station-years of data were entered into the PSMSL database, increasing the total PSMSL data holdings to over 70000 station-years. In addition, the PSMSL, together with the British Oceanographic Data Centre (BODC), are responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly values and higher frequency) from the Intergovernmental Oceanographic Commission's Global Sea Level Observing System (IOC's GLOSS) core network.

New and updated products have been made available over the last four years. These include:

- an improved relative sea level trends product by adding maps showing estimated seasonal cycles and number of years required to obtain a sea level trend of a given uncertainty;
- working with Système d'Observation du Niveau des Eaux Littorales (SONEL) to offer information about the geocentric height and rate of vertical movement of some tide gauges;
- updating some of the longest time series to account for the differences between Mean Tide Level (MTL) and mean sea level and adding a flag to indicate occurrence of MTL values;
- making data available from *in situ* ocean bottom pressure recorders from all possible sources;
- enhanced de-drifting code for ocean bottom pressure recorders added to website;
- development of automatic quality control software for tide gauge data.

PSMSL staff have continued to be active in a variety of international meetings, working groups, conferences and workshops over the last 2 years including those organised by the Global Geodetic Observing System (GGOS), IOC GLOSS, European Geophysical Union (EGU), EuroGOOS, and International Marine Data and Information Systems (IMDIS). In addition, PSMSL has answered many enquires relating to sea level and have appeared on radio and television discussing aspects of sea level change. PSMSL staff have also co-organised and contributed to tide gauge and sea level training courses. Annually statistics are collated on the number of peer-reviewed published papers that use the PSMSL dataset. Over the last six years there are over 400 papers in 116 distinct journals, and the number of citations has increased to around 70 citations per year.

1 Introduction

The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognised global sea level data bank for long-term sea level change information from tide gauges and bottom pressure recorders. Established in 1933 by Joseph Proudman, who became its first Secretary, the PSMSL is responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges and also provides a wider Service to the sea level community. The PSMSL is part of the National Oceanography Centre (NOC) at Liverpool, and receives funded by the Natural Environment Research Council (NERC, a component of UK Research and Innovation).

The PSMSL reports to several bodies which operate under the auspices of the International Science Council (ISC) including the International Union of Geodesy and Geophysics (IUGG), the International Association for the Physical Sciences of the Oceans (IAPSO), including its Commission on Mean Sea Level and Tides (CMSLT). PSMSL is a service of the International Association of Geodesy (IAG) and contributes to the IAG Global Geodetic Observing System (GGOS). PSMSL also has a key role in the Intergovernmental Oceanographic Commission's (IOC's) Global Sea Level Observing System (GLOSS).

Towards the end of 2015, the PSMSL was accepted as a regular member of the International Science Council's World Data System (ISC-WDS). The ISC-WDS has a rigorous application process and PSMSL was very pleased to gain membership to this interdisciplinary body, showing that the PSMSL is regarded as a trustworthy facility in terms of authenticity, integrity, confidentiality and data availability and services. The goal of the ISC-WDS is to create and co-ordinate global 'communities of excellence' for scientific data services.

The primary aim of the PSMSL is the provision of the global databank for long-term sea level information from tide gauges. PSMSL has continued to increase its efforts in this regard and over the last four years almost 10000 station-years of mean sea level data were entered into the PSMSL database, increasing the total PSMSL data holdings to over 70000 station-years from over 2350 stations. In addition, the PSMSL, together with the British Oceanographic Data Centre (BODC), is responsible for the archive of delayed-mode higher-frequency sea level data (e.g. hourly or higher frequency values) from the IOC's GLOSS Core Network.

The PSMSL database contains monthly and annual mean values of sea level. The dataset and ancillary information are provided free of charge and are made available to the international scientific community through the PSMSL website (www.psmsl.org). Accompanying metadata includes station descriptions and their locations, types of instrumentation and, where available, frequency of data collection as well as notes on other issues of which users should be aware (e.g. earthquakes that are known to have occurred in the vicinity or subsidence due to local groundwater extraction). As ever, we are very grateful to our data suppliers (Annexes 1 and 2 list the countries and organisations which have supplied data during the reporting period). The PSMSL mailbox psmsl@noc.ac.uk responds to requests for information from national tide gauge agencies, decision makers (local councils, Parliamentary enquiries), the media and the general public.

2 Sea Level Futures Conference

PSMSL reached its 85th anniversary in 2018, and celebrated its long history of providing mean sea level records from tide gauges by hosting an international meeting. The "Sea Level

Futures" Conference, attended by over 100 delegates (Figure 1) from 65 international organisations, was dedicated to examining the current state-of-knowledge of sea level research, and discussed the developments in observational networks and technology required over the next ten years to allow the community to continue enhancing understanding of global and regional sea level rise and variability.

Figure 1: Sea Level Futures Conference attendees

Current sea level science provides clear evidence that sea level is rising and this is already impacting coastal areas. Addressing the challenges for the coastal areas in a warming climate requires integrated, sustainable and continued observations, data products and advanced modelling capability. Conference participants recognised the need for close collaboration between scientists from different disciplines and the stakeholder community to develop a response to sea level change and implement measures to adapt to and mitigate its effects.

The key recommendations are summarised in a conference statement.

3 Prof. Philip Woodworth elected as an IUGG Fellow

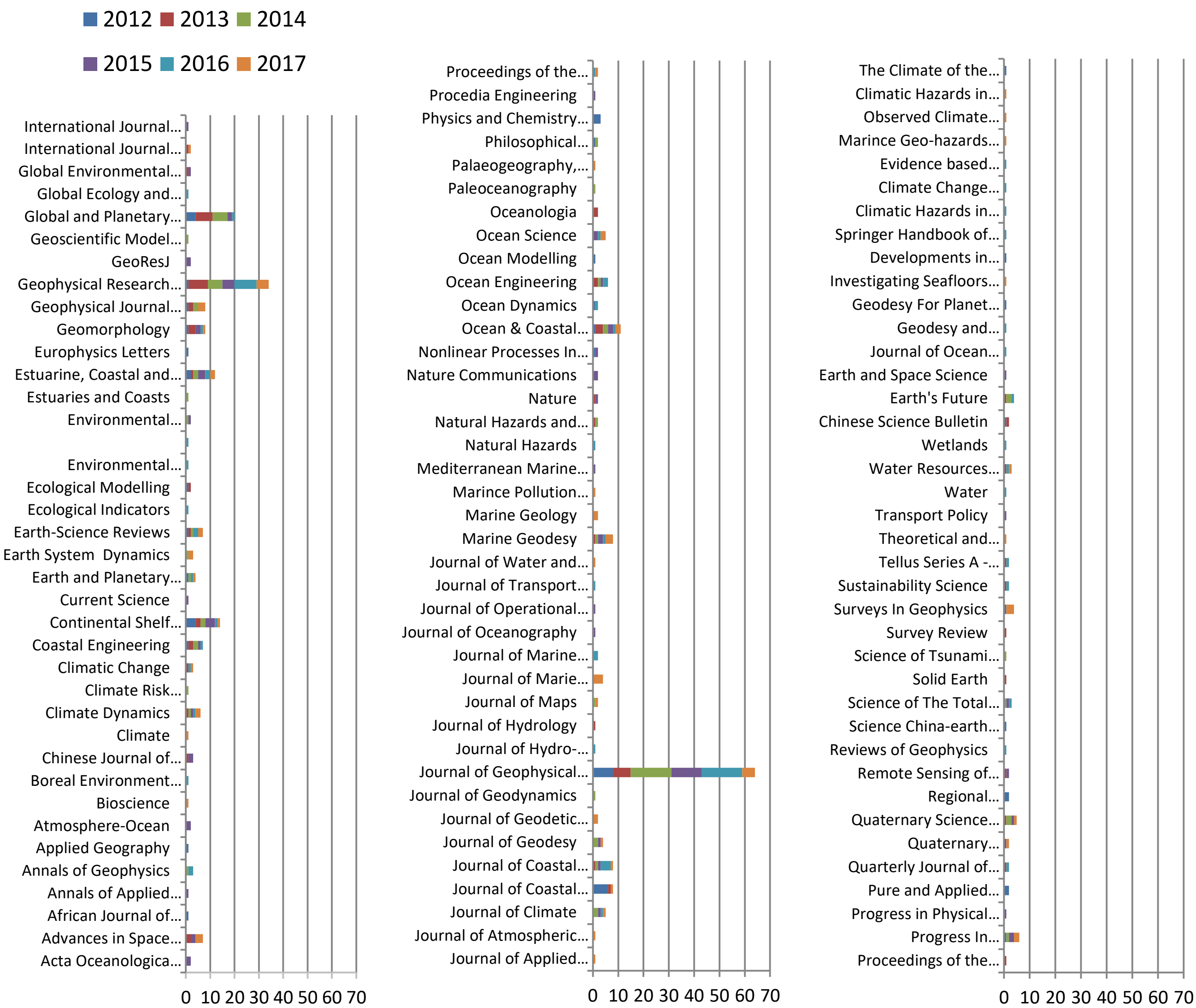
PSMSL is pleased to announce that Prof. Philip Woodworth has been elected as an IUGG Fellow – this will be formally bestowed by the IUGG President at the Award Ceremony of the XXVII IUGG General Assembly on 13 July 2019 in Montreal, Canada. Fellowship of the IUGG is a tribute, awarded by the IUGG Bureau, to individuals who have made exceptional contributions to international cooperation in geodesy or geophysics and attained eminence in the field of Earth and space sciences (IUGG by-law 22).

Prof. Woodworth was Director of the PSMSL for many years, and through promotion of the PSMSL and publications across a range of topics (underpinned by PSMSL data), he has contributed to research on sea level variability on a wide range of time scales. His work with rare historical data sets has put the changes seen during the 20th and 21st centuries into a long-term context, in particular helping to estimate acceleration of sea level rise. His work has benefited research and international communities in the fields of past sea level change, climate change, ocean circulation and tides, coastal processes, vertical crustal motions at coastlines, geology, geodesy and calibration of altimetry systems. He is currently an Emeritus Fellow of the National Oceanography Centre and Visiting Professor, Liverpool University School of Environmental Sciences.

His IUGG citation reads: “Woodworth, Philip (UK) for his significant advancement of sea-level science and outstanding contribution to international scientific cooperation, especially his leadership of the Permanent Service for Mean Sea Level (PSMSL).”

4 Number of Citations for PSMSL data series for the period 2012-2017

Annually PSMSL collates statistics on the number of peer-reviewed published papers that use the PSMSL dataset. We do this in a number of ways. Firstly, we find papers that have cited either Holgate *et al* [2013] or Woodworth and Player [2003] in Web of Science and Scopus. Not all papers will have cited either of these papers so we also perform full text searches for “PSMSL” or “Permanent Service”. These papers are then manually filtered to remove any papers that are not actually referring to PSMSL. We note that it is very easy to miss papers that use our dataset but have not referred to us directly so our statistics are likely to be biased low. Figure 2 below shows the statistics for the last six years. There are over 400 papers in 116 distinct journals ranging from a variety of subject areas including oceanography, quaternary research, geodesy, climate, environment and multidisciplinary. The top three journals in terms of total publications are Global and Planetary Change (20; JCR impact factor 3.548); Geophysical Research Letters (34; JCR impact factor 4.456) and Journal of Geophysical Research (64; JCR impact factor 3.318). Other notable citations come from Nature (2; IF 38.138), Nature Communications (2; IF 11.329), PNAS (1; 9.423), and Reviews of Geophysics (1; 11.444). There were over 73 citations in journals with impact factors greater than 4.



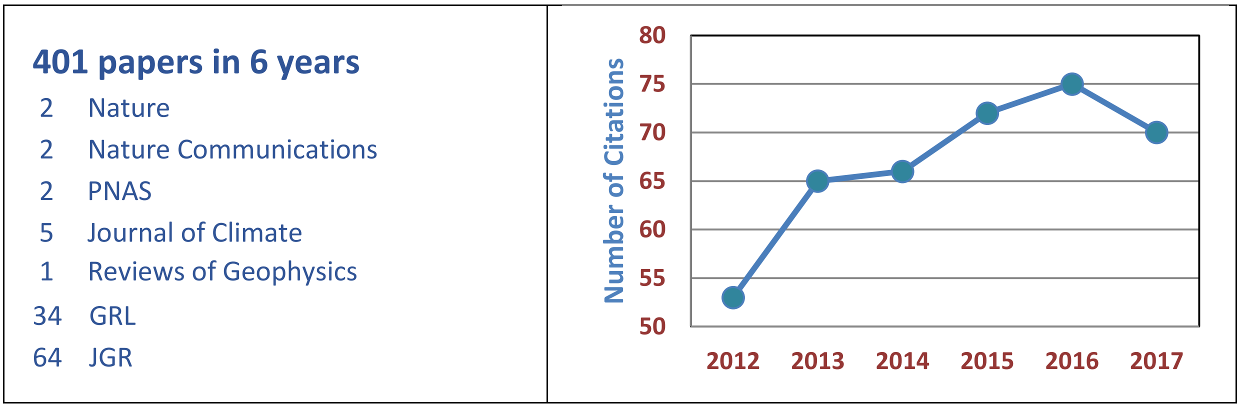


Figure 2: Statistics of PSMSL Data Set Citations

5 Mean Sea Level Data received

Figure 3 shows the amount of data received by the PSMSL since 2014 indicating how many station years have been added to the database each year and from how many stations. The number of active stations remains at about 800, but the number of station years can vary considerably from year to year. This may be due to a data provider reviewing and resupplying their historical dataset or if a backlog of data has been supplied.

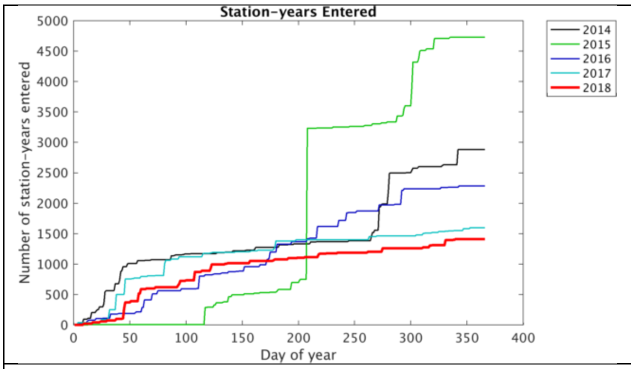


Figure3a: Number of station years added to the PSMSL database during 2014-2018

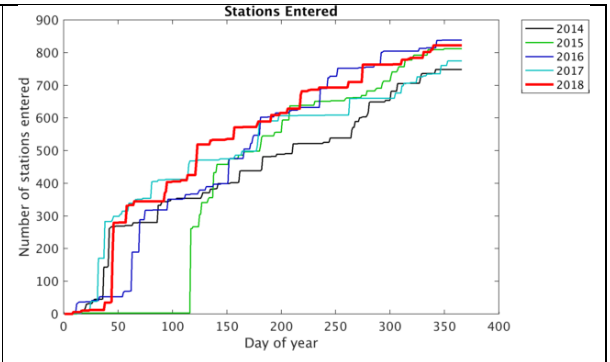


Figure 3b: Number of stations with data added to PSMSL database during 2014-2018

Figure 4 shows the stations which have provided data during 2018, or in 2017 (but not 2018). 815 stations have provided data in 2018, with a further 111 providing data in 2017. These can all be considered as active stations, but there are many stations for which no data have been supplied for many years. Some of these have undoubtedly ceased to operate; for others contact with the operators is being actively pursued. New stations are providing near-real-time data for tsunami monitoring, but a number of these do not yet supply quality controlled mean sea level values to the PSMSL; these are also being sought to add to the dataset.

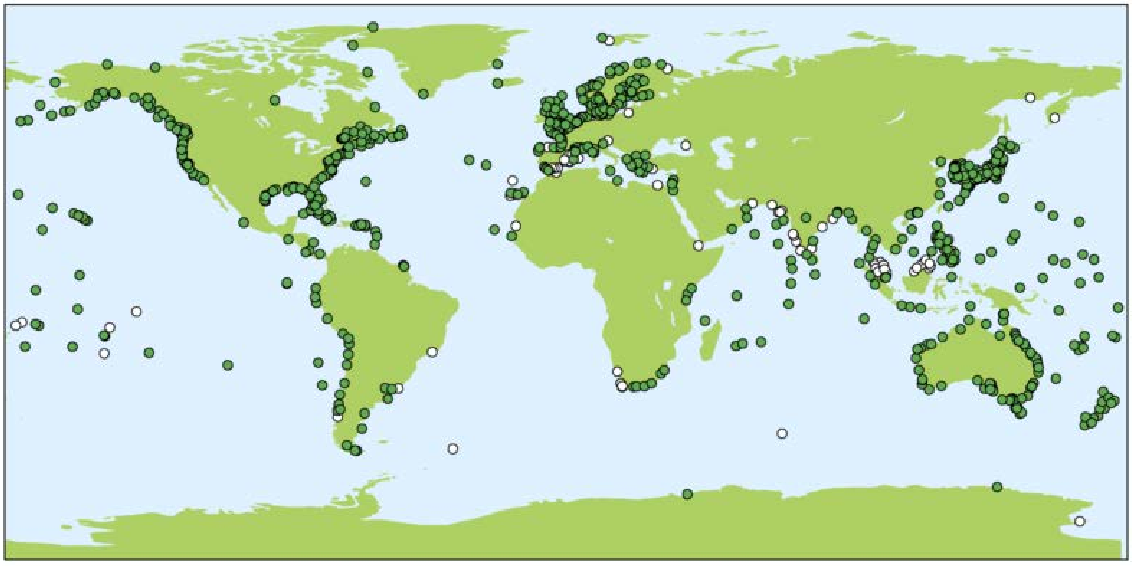


Figure 4: New data received by PSMSL during 2017-18

Figure 5 gives a more detailed view of the data held by PSMSL, indicating where data were supplied in the past – in particular, the decline in the number of stations in the Arctic is noticeable. However, many regions regularly supply mean sea level data (e.g. North America, Europe, Japan, Australia, New Zealand, South Africa, India), but there are still gaps in data receipts from the Arctic and Antarctic, parts of South East Asia, South and Central America, and Africa; these are presently being targeted to try to improve data flow. African countries received special attention through the Ocean Data and Information Network for Africa (ODINAfrica) projects and the Indian Ocean Tsunami Warning System (IOTWS), but many of these are no longer operating satisfactorily.

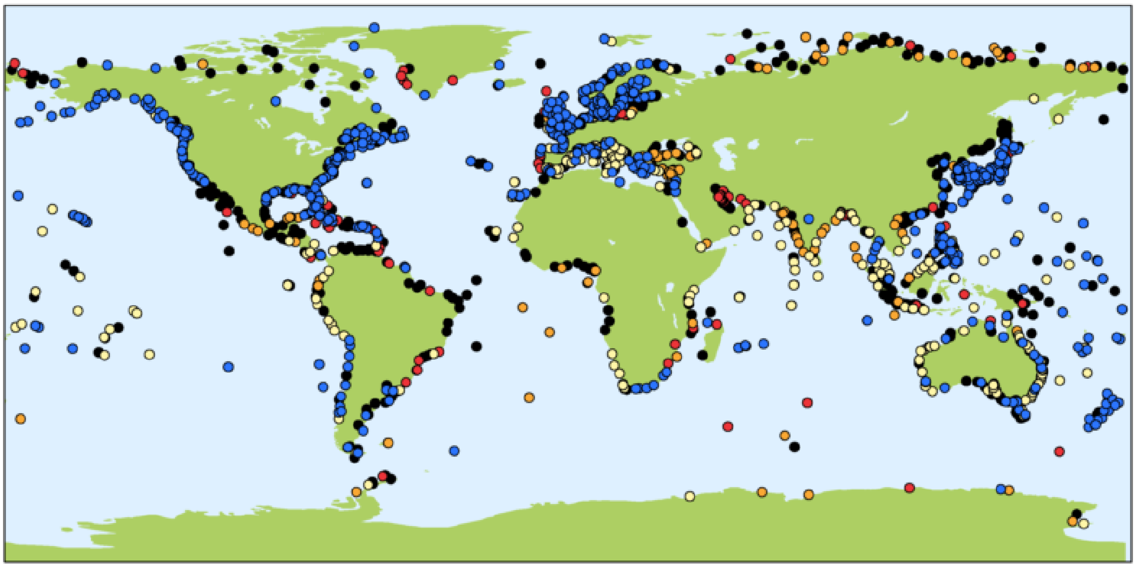


Figure 5: Year of most recent data received by PSMSL

In Figure 6 below, the uneven distribution of data supply is further illustrated; pale blue shows the data receipts from the Northern Hemisphere while the dark blue area of the plot shows the data receipts from the Southern Hemisphere.

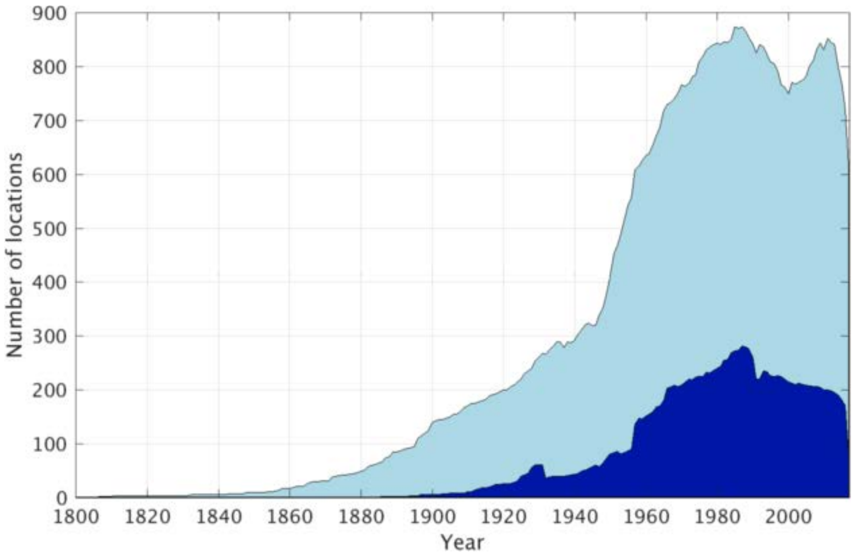


Figure 6: North-south hemisphere distribution of data received by PSMSL

The distribution of the longest time series also reflects this, as shown in Figure 7. The Southern Hemisphere has only a small number of time series of over 100 years; most are found in the Northern Hemisphere. Overall western Europe, North America and Japan have most of the longest records, and also have a high proportion of records of 50 to 100 years, although Australia, New Zealand, South Africa, Chile and Argentina also have a number of records of this length. The Arctic and Antarctic have very few records of greater than 50 years, and a number of the Russian Arctic tide gauges are no longer operational.

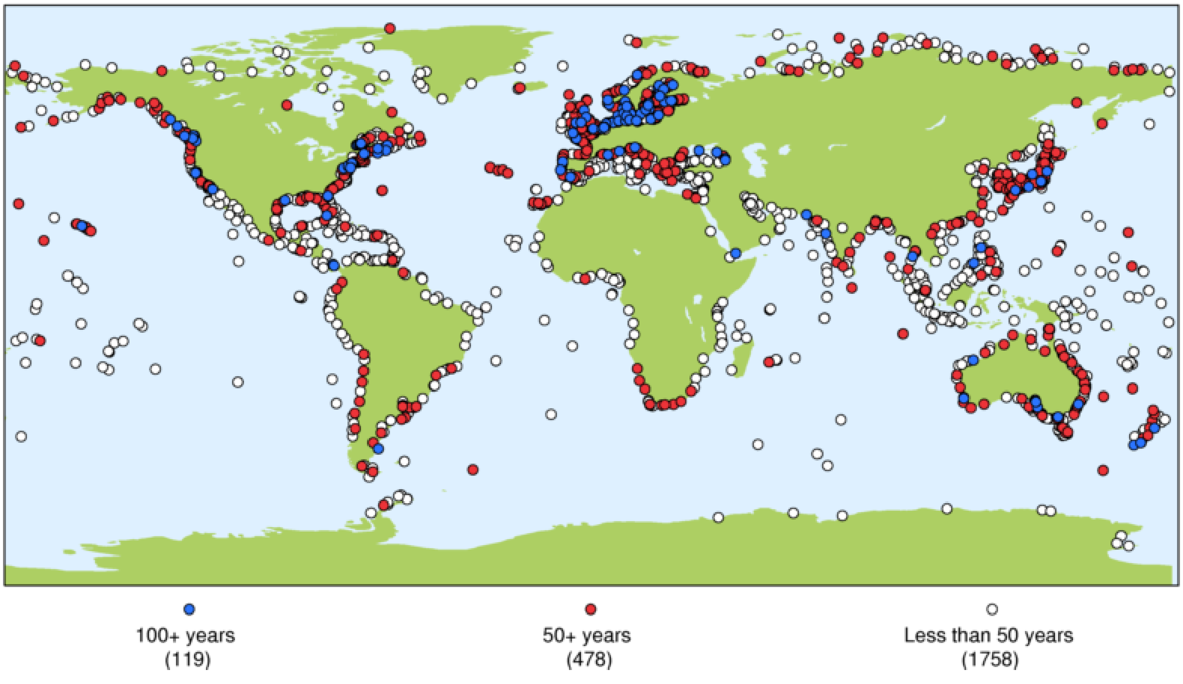


Figure 7: Distribution of long tide gauge records

6 Changes to Mean Sea Level Time Series with some Mean Tide Level values

PSMSL has introduced a change to some of the longest time series held in the database. In some older time series, the sea level values were reported as means of high and low waters, typically called Mean Tide Level (MTL). This is in contrast with the average of higher frequency readings taken over the entire tidal cycle, which is called Mean Sea Level (MSL). As these differ, this could introduce an artefact into estimates of the long-term trends where a time series includes both types of value. To improve transparency in these combined records, and to cause the minimum disruption to the current set of records, a flag has been introduced indicating MTL values in a MSL record and an estimate of the annual average difference (MTL-MSL) has been added to the Revised Local Reference (RLR) time series. More detail of the changes is available on the PSMSL website.

7 Author Archive

During 2016, Peter Hogarth has liaised with Prof. Philip Woodworth to work on some of the historic data series available through the PSMSL. As a result, he has recently published an article in Journal of Geophysical Research investigating acceleration of sea level rise. In the course of this research, he has extended the tide gauge time series available for several locations. He has made available to us his extensive notes and the additional data.

8 Global Sea Level Observing System (GLOSS) Core Network Status

The GLOSS was established by the IOC in 1985 to provide coordination for global and regional sea level networks in support of, and with direction from, the oceanographic and climate research communities. Various tide gauge networks have contributed to GLOSS, each with a different focus and each changing over time as research and operational priorities evolve.

The main component is the GLOSS Core Network (GCN), a global set of 290 tide gauge stations (Figure 8) that serves as the backbone of the global *in situ* sea level network. The network is designed to provide an approximately evenly distributed sampling of global coastal sea level variation. Ideally, each station should provide data on a variety of timescales for use in different applications; for example, real-time data can be useful for tsunami monitoring, whereas monthly and annual mean data can be used to monitor long-term changes in sea level. In addition, sites should also be fitted with GNSS equipment to monitor land movement at or near the site. Further information on GLOSS is available in the GLOSS Implementation Plan 2012 and on the GLOSS website (www.gloss-sealevel.org).

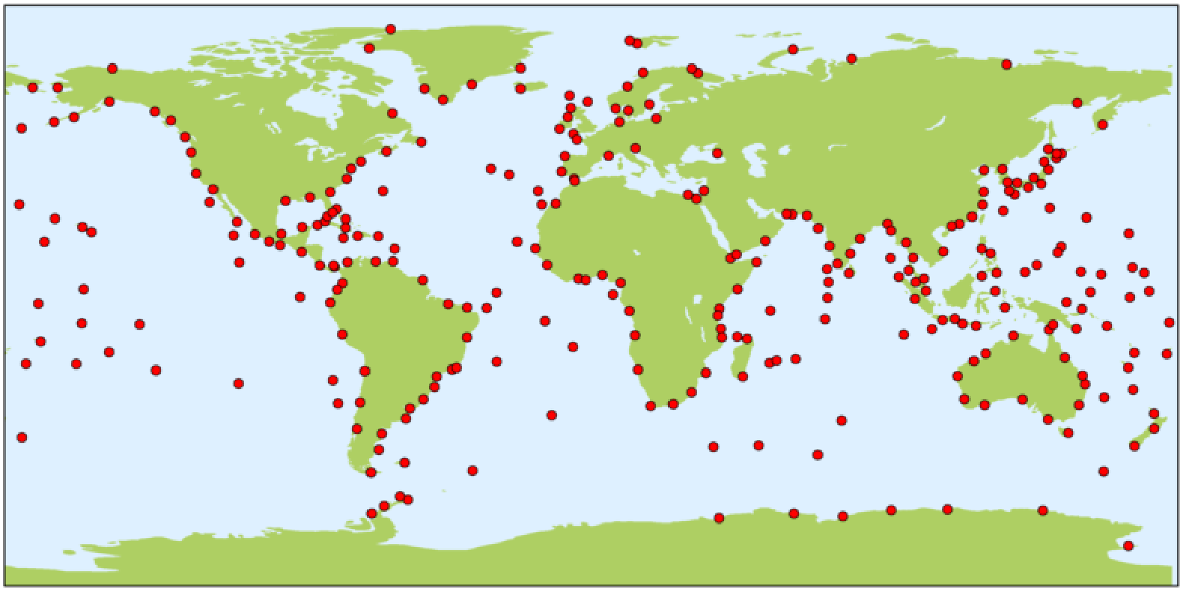


Figure 8: GLOSS Core Network

For many years PSMSL has produced maps showing the status of the Core Network from its perspective, and more recently has been generating additional maps, automatically updated weekly, showing the status for the other GLOSS data streams (e.g. real-time, fast-mode, delayed-mode and TIGA/GNSS). Figure 9 presents how PSMSL currently sees the status of the GLOSS Core Network. The map indicates whether a station is considered currently operational (green marker), has been operational in the past (orange marker), or has never operated successfully (white marker). Figure 10 shows the development of the GCN in terms of sites providing mean sea level data to the PSMSL from 1989 through to 2018 – a period of almost 30 years. The figure also includes changes to the definition of the GCN over time.

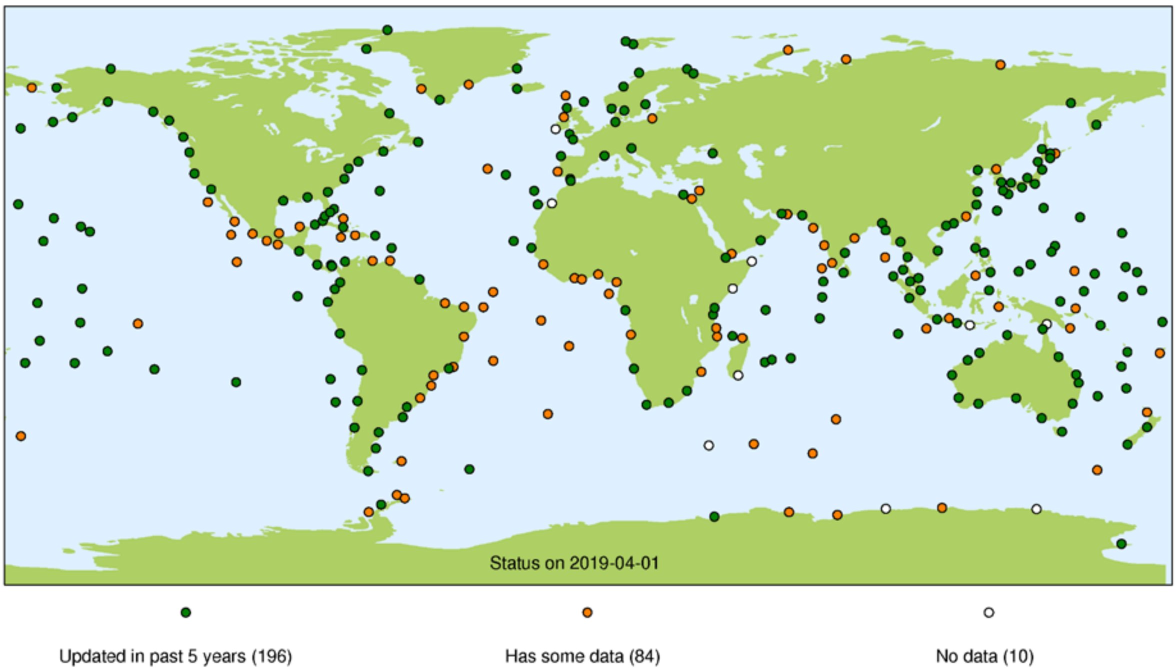


Figure 9: GLOSS Status from a PSMSL perspective

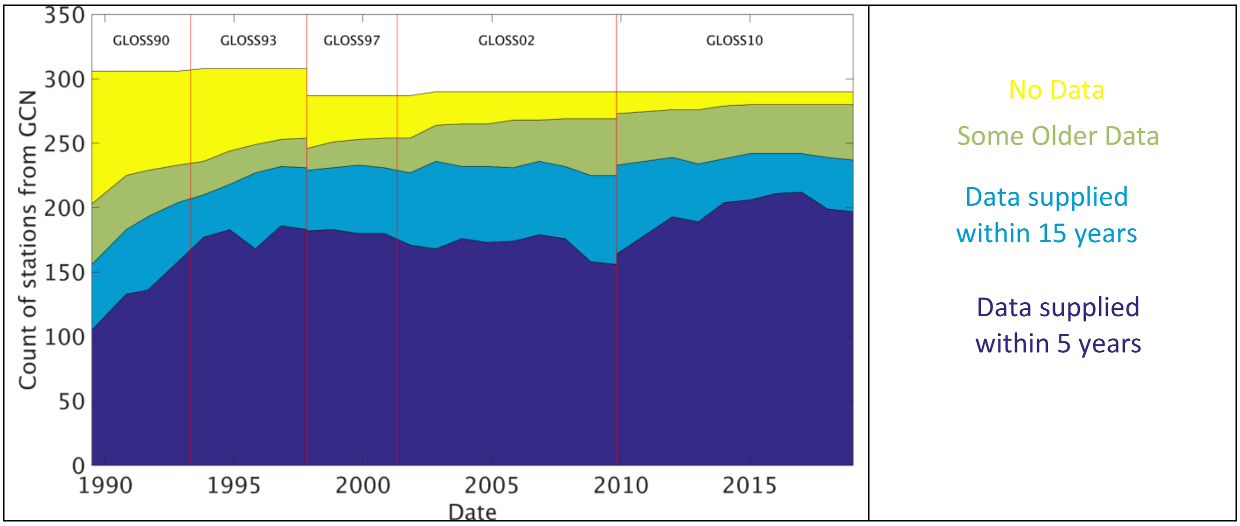


Figure 10: Status of GLOSS Core Network from a PSMSL perspective (1989-2018)

9 Data Archaeology in collaboration with GLOSS

PSMSL has taken the lead in data archaeology through the IOC GLOSS programme. The GLOSS data archaeology sub-group, under the leadership of Elizabeth Bradshaw, is collating tools and guidelines for the scanning, digitising and quality control of historical tide gauge charts and sea level ledgers. To further this effort she participated remotely in the Research Data Alliance (RDA) 10th Plenary Meeting in September 2017 including the Data Rescue Interest Group session and the 11th International Atmospheric Circulation Reconstructions over the Earth (ACRE) workshop (November 2018) where she gave a presentation on the status of GLOSS data rescue activities and links with the meteorological community.

Figure 11 shows some of the recent data rescue activities over the last 5 years. The red dots on the map are data recovered through data rescue activities. As well as numerous records in Europe, there have been newly digitised data from data sparse regions such as Dakar in Africa (36 years starting in 1902), St. Helena in the South Atlantic (1826 - 1827), Newcastle and Williamstown in Australia and Mawson and Cape Denison in Antarctica (months in the form of paper charts). In addition, Talke and Jay (2017) provides an update to the data rescue work carried out by Stefan Talke and team and includes sites not covered by the above map. Very recently PSMSL has received a dataset rescued from Porto Corsini/Marina di Ravenna, Italy (Bruni, S., et al, 2019).

However, many historical tide gauge data still exist in non-digital form. These mostly paper-based datasets are of great potential value to the sea level community for a range of applications, the most obvious being the extension of existing sea level time series as far back as possible in order to understand more completely the timescales of sea level change. In the future, coordination of a tide gauge data rescue project with ACRE programme could result in interesting synergies. The other major form of analogue sea level data is handwritten ledgers. Transcribing these is labour intensive and usually undertaken by people entering numbers by hand. GLOSS is exploring other methods for use in the future; one possibility is to have a Citizen Science approach as with the OldWeather project run in partnership with ACRE. An alternative approach is to investigate the adaption of Handwritten Text Recognition technology for use with handwritten tide gauge ledgers. Lack of funding and the time consuming nature of data rescue (manual digitisation, seeking accompanying metadata) continue to be barriers.

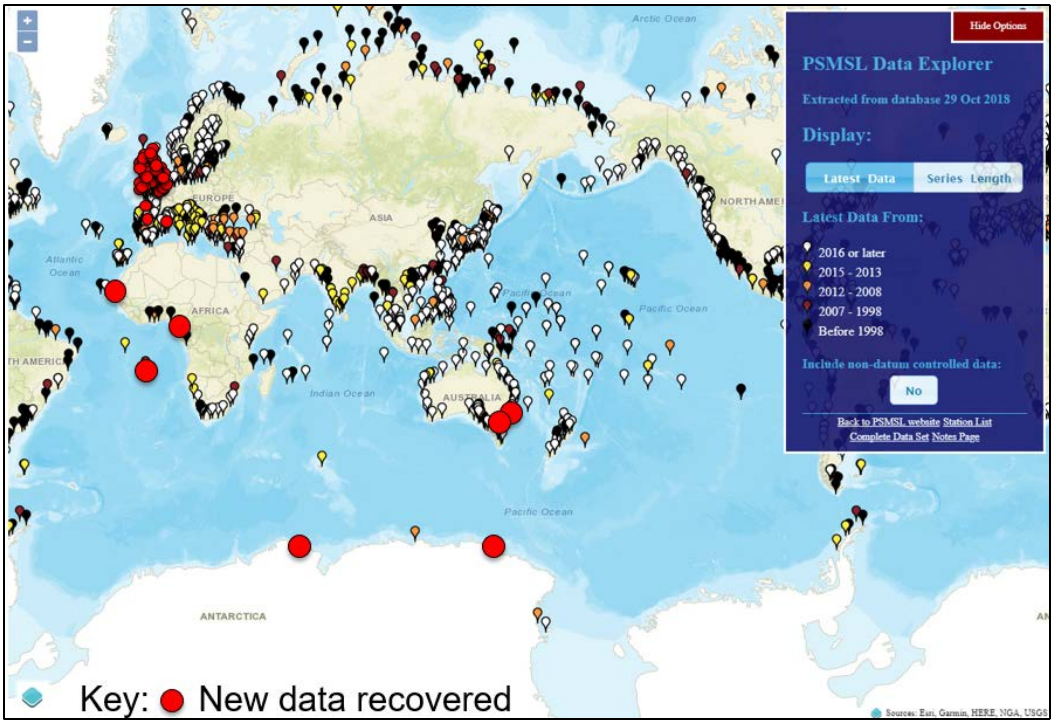


Figure 11: Sea level data rescue activities in the past 5 years

References:

Talke, S. and Jay, D., 2017. Archival Water-Level Measurements: Recovering Historical Data to Help Design for the Future. *Civil and Environmental Engineering Faculty Publications and Presentations*. 412.

Bruni, S., Zerbini, S., Raicich, F. and Errico, M., 2019. Rescue of the 1873–1922 high and low waters of the Porto Corsini/Marina di Ravenna (northern Adriatic, Italy) tide gauge. *Journal of Geodesy*, pp.1-18.

10 Global Extreme Sea Level Analysis (GESLA)

The Global Extreme Sea Level Analysis (GESLA) project grew out of the interest of several people in learning more about changes in the frequency and magnitude of extreme sea levels. The first GESLA dataset (GESLA-1) was assembled by Philip Woodworth (National Oceanography Centre, Liverpool), Melisa Menendez (University of Cantabria) and John Hunter (University of Tasmania) around 2009 and contained a quasi-global set of 'high frequency' (i.e. hourly or more frequent) measurements of sea level from tide gauges around the world.

GESLA-1 was used first in a study of sea level extremes by Woodworth and Menendez (JGR, 2010). It has since been used in a number of other published studies of extremes including the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

After some years it became apparent that GESLA-1 needed updating, which has resulted in the present GESLA-2 dataset comprising 37000 station years of information from 1300 stations (as of February 2016). The three original people have been joined in GESLA by

Marta Marcos (University of the Balearic Islands) and Ivan Haigh (University of Southampton).

It can be seen that, while the study of extreme sea levels has been the main interest, the availability of as large a quasi-global sea level dataset as possible enables many other types of study, such as changes in ocean tides. The oceanographic community needs a global dataset such as GESLA, that is regularly updated and extended to include new historic data as it becomes available. Steps are underway to see how that might be accomplished in the future.

11 Developing a more structured and standardised approach to descriptive metadata

PSMSL has carried out a major redesign and reprogramming of its database. This has greatly expanded both the amount and level of structure within the metadata. In particular, the database now contains information about the links between the local tide gauges datums and national vertical datums. National vertical datums are linked to the EPSG registry, and will be linked to the ISO Geodetic Registry once it has been completed. Extra metadata from the database is gradually being added to the PSMSL website and distributed data files.

Soon the data will be released in netCDF format, which will make more of this structured metadata machine readable. In addition, PSMSL is working with other providers of tide gauge data to develop ways of distributing tide gauge data using internationally agreed standards.

12 Interactive map showing long-term trends

The web pages illustrating the trends in the tide gauge data set, as well as yearly variation of sea level with respect to an average (sea level anomalies), currently use the 10 Jan 2017 release of the data set. The interactive map showing fitted trends now uses a better statistical model that accounts for autocorrelation in the time series, allowing us to produce realistic estimates of error in the trends. There is also an estimate of the number of years required at each station to produce a trend with an uncertainty of 1.0, 0.5 and 0.1 mm/year.

Both the estimated trend and the uncertainty will change as one changes the time span chosen by moving the sliders. Secondly, in order to calculate these results, monthly means are now used instead of annual means. The trends also now use the corrected data which was measured using Mean Tide Level rather than Mean Sea Level. Example trend maps are shown below (Figure 12).

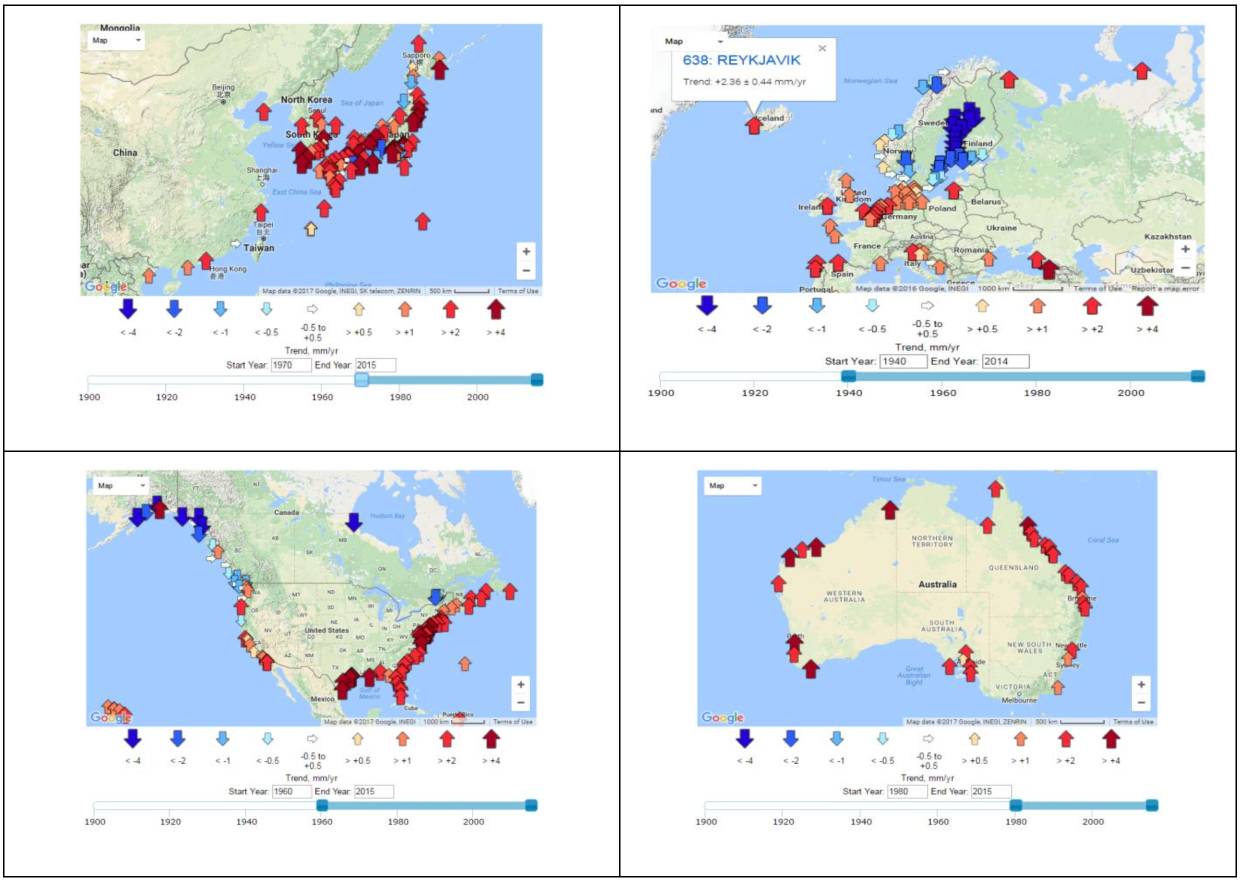


Figure 12. Interactive Relative Sea Level Trends Map

The relative sea level trends product has been further enhanced (Figure 13) by adding maps showing the estimated [seasonal cycles] and [number of years required to obtain a sea level trend of a given uncertainty.]

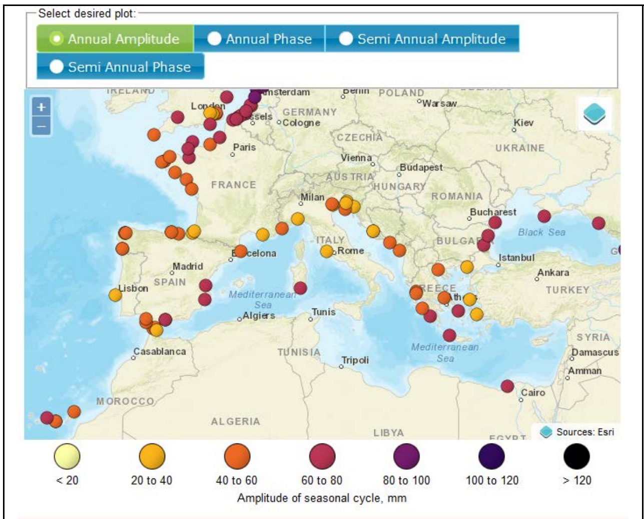


Figure 13a Estimated seasonal cycles

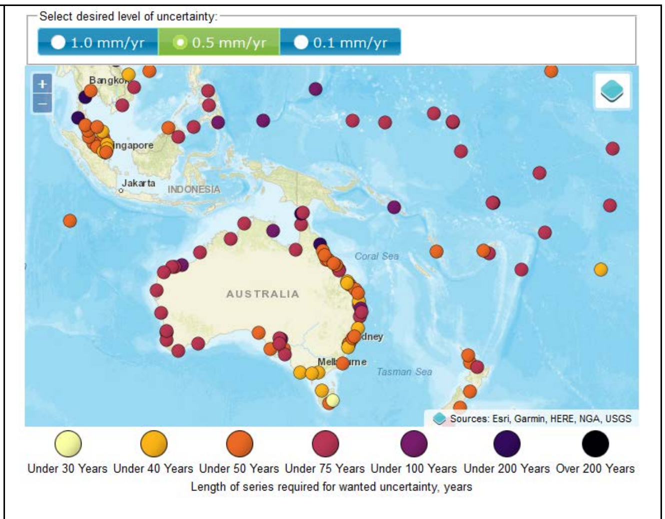


Figure 13b: Series length required for selected level of uncertainty

13 Ellipsoidal Links for Revised Local Reference Data

The mean sea level data distributed by PSMSL are heights above a local datum. For the Revised Local Reference (RLR) dataset, the stability of the local station datum is ensured by fixing its height to a geodetic benchmark assumed to be on reasonably stable ground. The measurements taken from tide gauges in this way are known as relative mean sea level; height is measured relative to the local land. As a result, the data can be affected by vertical movement of the land.

For some analyses we may wish to attempt to remove the land movement signal from the tide gauge record, for example, for reconstruction of historical global mean sea level, or to compare sea level measured by tide gauges with sea level measured by satellite altimetry. One solution to both of these cases is to use continuous Global Navigation Satellite System (GNSS) measurements from a receiver located near the tide gauge. The GNSS receiver measures heights relative to an ellipsoid and can be used to estimate the rate of vertical movement of the local land mass. The tide gauge datum can be associated with these estimates if routine geodetic levelling campaigns are carried out between the tide gauge benchmark and the GNSS receiver.

PSMSL continues to work with Système d'Observation du Niveau des Eaux Littorales (SONEL), the GLOSS data centre for GNSS measurements, to offer information about the geocentric height and vertical rate of movement of some tide gauges. These estimates are dependent on linking the tide gauge's primary benchmark with the GNSS receiver through levelling. As a result, these are currently only available at small subset of stations. The details of the link are shown on the station's RLR diagram page and a fuller description of the work is available here. The reference ellipsoid used for the University of La Rochelle GPS solutions is GRS80. The available information has been improved using feedback from users: for example, we have created a table of all sites where a tie has been established.

14 Release of Bottom Pressure Recorder de-drifting code

As requested by IAPSO, PSMSL archives bottom pressure recorder data. When bottom pressure recorders are deployed, readings drift over time. It is impractical to recalibrate the instrument mid-deployment, so an estimate of the drift must be removed before the data can be used.

The common approach has been to fit a short-term exponential drift, combined with a longer-term linear drift. However, the accuracy of this fitted drift can be improved by first removing all known annual or longer period fluctuations, such as changes due to the pole tide. As part of a recent project, software has been developed which attempts to improve de-drifting by removing these fluctuations.

The PSMSL website now contains a link to the Matlab code developed: this code will have wider uses, as it includes functions to can calculate the long-period equilibrium tides and the polar tide. Please note that this technique cannot separate instrumental drift from any other secular trend, so recorders subject to this drift cannot be used to derive sea-level trends.

15 Development of automatic quality control software

The PSMSL continues to be involved with developing training information and organising training courses, for operators of tide gauges and users of their datasets. As part of a project funded by the UK Foreign and Commonwealth Office supporting small island states, PSMSL were tasked with developing prototypes for automatic quality control software for tide gauges, and a simple data portal for distributing tide gauge data and sea level information. The outputs are now available at https://psmsl.org/cme. The automatic quality control software uses MATLAB, and includes code to carry out tidal analysis and create tidal predictions. We have plans to keep developing the quality control software in the future, including creating a version in Python.

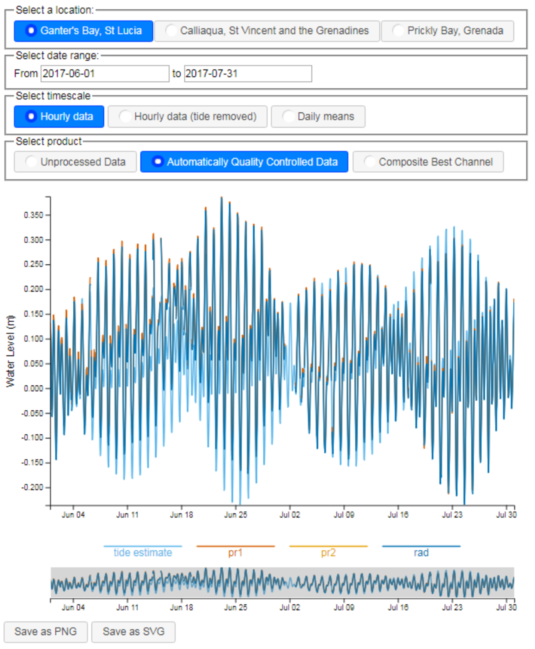


Figure 14: Data plotter output of the automatic quality control process

Figure 14 illustrates the data plotter outputs of the quality control process. The user can select output from one of three tide gauges in the Windward Islands, and choose to display hourly data (maximum one year), hourly data with the fitted tide removed, or daily means. Display options are unprocessed data (data before the quality control is applied), automatically quality controlled data, and a "composite best channel" option, where the algorithm combines output flagged good from all available sensors at a site into a single series. An estimate of the fitted tide is included if hourly and quality control data options are selected.

The plot can be zoomed and panned using a mouse, or by resizing the grey rectangle in the small overview plot at the bottom of the figure. The image can be saved in raster (.png) or vector (.svg) formats using the buttons at the bottom of the plot.

16 Ground based GNSS - Multipath Reflectometry (GNSS-MR)

Simon Williams has been involved in recent studies that have demonstrated the utility of ground based GNSS Multipath Reflectometry (GNSS-MR) for sea level studies. GNSS receivers suffer from multipath (Figure 15), but if the physical and geometric effects multipath has on the measured signals are understood then this knowledge can be used to measure other environmental parameters.

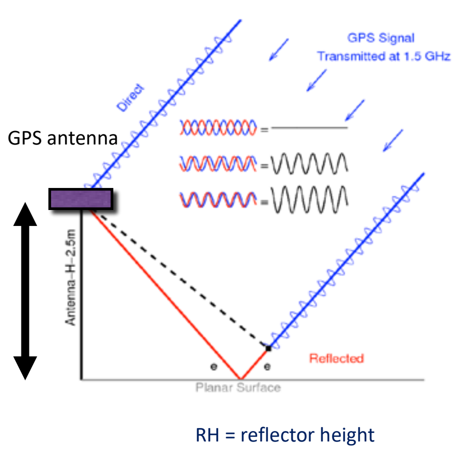


Figure 15: GNSS-MR Schematic

Two Current Projects are underway on GNSS-Multipath Reflectometry:

1. Comparison of GNSS-MR and Satellite Altimetry (GOCE++ CCN), with DTU, Denmark

   This is an example from one of the first “accidental” sites (i.e. not installed to do this), Peterson Bay in Alaska. There are three signals from different satellites passing over at different tidal states: low tide (so closer to the antenna), mid-tide and high tide, further from the antenna. We see that we have different frequencies – higher frequency for a larger reflector height. These signals can be taken and run through a Lomb-Scargle periodogram (power spectrum) and pick the peak – which is the reflector height. Conclusions so far indicate that ground based GNSS-MR using pre-existing geodetic quality equipment can measure sea level remotely with a daily accuracy of around 2-3 cm and a monthly accuracy of about 1-2 cm. There is some bias in the results – probably due to the antenna phase centre.

2. LocTIPS: Low Cost GNSS Tide & Sea Level Measurements for Inter-tidal Public Safety (with co-workers at NOC)

   A recent NERC-funded proof of concept award has successfully demonstrated that GNSS signals reflected off the sea surface and received by very low cost (£100) receivers can be used to estimate the difference in height between the receiver and the water rather than a geodetic quality one (~£10k) – with an antenna designed to reduce multipath. This represents a method of remotely sensing tidal elevations and, if averaged over time, mean sea level. This project is in collaboration with the Royal National Lifeboat Institution (RNLI) to provide tidal information for predicting when people can safely travel to and from Coney Island, Sligo, Ireland, over the strand (beach). The results so far compare well with tide gauge measurements (Figure 16). Results look favourable with an accuracy similar to that of the geodetic receivers. There is also the potential to measure other environmental variables (e.g. wave height, beach profiles).

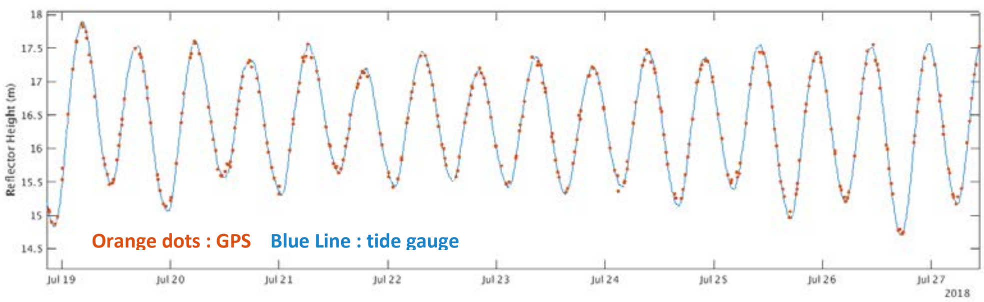


Figure 16: GNSS-MR results compared to tide gauge observations

17 PSMSL Staff and Advisory Group

Primary funding for PSMSL comes from NERC *via* the NOC; other projects provide small amounts of funding. Between 2015 and 2016 this has been approximately equivalent to 3 full time staff, but during 2017 and 2018 this decreased to the equivalent of 2 full time staff, however in reality all of those listed in the table below have contributed to PSMSL. As ever, we are grateful to others in the NOC Sea Level and Technology Groups who contribute to, or represent PSMSL at, meetings, conferences, or other fora. We have said goodbye to Mark Tamisiea who left PSMSL has returned to the USA. During his time with us, he made a considerable contribution to PSMSL and he will be missed. However, he has generously continued to represent PSMSL at some GGOS meetings.

Dr. Lesley Rickards, Director	Dr. Angela Hibbert, Capacity building
Mrs. Kathy Gordon, Data Manager	Dr. Svetlana Jevrejeva, Principal Scientist
Dr. Andrew Matthews, Data Scientist	Dr. Simon Williams, Senior Scientist
Miss Elizabeth Bradshaw, Data Scientist, BODC	Prof. Philip Woodworth, Scientific Advisor

Lesley Rickards, who has been PSMSL Director since 2007, has recently stepped down from this role. She is replaced by Elizabeth Bradshaw, who has worked alongside the PSMSL for many years. Kathy Gordon and Andrew Matthews continue in their current roles and Svetlana Jevrejeva has continued to act as the principle PSMSL scientist. However, she is just starting a two year sabbatical at the Centre for Climate Research of Singapore.

The PSMSL is also served by an Advisory Group which at present consists of: Dr. R. Neilan (JPL, USA), Prof. G. Mitchum (University of South Florida, USA), Dr. Guy Wöppelmann (Université de La Rochelle, France), Dr. P. Knudsen (Danish National Space Institute), Dr. R. Bingley (Nottingham University, UK), Dr. Begoña Perez Gomez (Puerto del Estados, Spain), Dr. Mark Tamisea (University of Texas, USA), and Dr. Thorkild Aarup (IOC, UNESCO).

18 Summary and forward look

PSMSL has continued to be active over the last four years with regard to important workshops and conferences, and busy with regard to data acquisition and analysis. The functions provided by the PSMSL are in as much demand as ever, and new products continue to be developed and activities have expanded. Future plans include:

- Improved integration of the mean sea level data set with sources of higher frequency data and improving the quality of accompanying metadata;
- Continued development of interoperable metadata formats for tide gauge data;
- Assess whether PSMSL follows FAIR data principles (Findable, Accessible, Interoperable, Reusable), and improve areas where we do not;
- Keeping contact with data suppliers (the trend being to acquire data from websites rather than direct supply) and ensuring that data made available in real-time are also contributed to PSMSL;
- Mint a digital object identifier (DOI) for the PSMSL dataset (in collaboration with BODC);
- Development of protocols concerning how sea level data recovered from historical records can be incorporated into the PSMSL dataset;
- Continue collaboration with SONEL (IAG TIGA Working Group data centre) and with GGOS;
- More information on the website about links between tide gauge datums and national datums and ellipsoids - available in both human and machine readable formats, using internationally agreed standards;
- Plan incorporation of sea level records measured using GNSS reflectometry into the PSMSL
- Contribute to ISC World Data System metadata catalogue and training pages
- Creation of software for automatic first level quality control of high frequency data
- Redesign and update of the content on the PSMSL website;
- Further develop data archaeology with the Group of Experts on GLOSS.

Annex 1: Stations received from individual countries 2015-2019

American Samoa		Malta
Antarctica		Marshall Islands
Argentina		Martinique
Australia		Mauritius
Bahamas		Mayotte
Bangladesh		Mexico
Belgium		Micronesia, Federated States of
Bermuda		Monaco
British Indian Ocean Territory		Myanmar
Canada		Namibia
Cape Verde		Nauru
Chile		Netherlands
China		New Caledonia
Cocos (Keeling) Islands		New Zealand
Colombia		Northern Mariana Islands
Cook Islands		Norway
Costa Rica		Oman
Croatia		Palau
Cuba		Panama
Curaçao		Papua New Guinea
Denmark		Peru
Dominica		Philippines
Dominican Republic		Portugal
Ecuador		Puerto Rico
El Salvador		Réunion
Fiji		Russian Federation
France		Saint Pierre and Miquelon
French Guiana		Samoa
French Polynesia		Senegal
Georgia		Seychelles
Germany		Singapore
Greece		Solomon Islands
Greenland		South Africa
Grenada		South Georgia & South Sandwich Is.
Guadeloupe		Spain
Guam		Sri Lanka
Haiti		Svalbard and Jan Mayen
Hong Kong		Sweden
Iceland		Tanzania, United Republic of
India		Thailand
Indonesia		Tonga
Isle of Man		Tuvalu
Israel		United Kingdom
Italy		United States
Japan		United States Minor Outlying Islands
Jersey		Uruguay
Kenya		Vanuatu
Kiribati		Viet Nam
Korea, Republic of		Virgin Islands, U.S.
Malaysia		Wallis and Futuna
Maldives		Åland Islands

Annex 2: Data Suppliers 2015 - 2019

Supplier	Country
Servicio de Hidrografia Naval, Argentina	Argentina
Australian Ocean Data Centre	Australia
National Tidal Centre	Australia
NSW Public Works	Australia
Agency for Maritime and Coastal Services	Belgium
Director of Hydrography and Navigation (DHN)	Brazil
Canadian Hydrographic Service	Canada
Servicio Hidrografico y Oceanografico de la Armada (SHOA)	Chile
National Marine Data and Information Service (NMDIS)	China
Hidrografski Institut, Split	Croatia
Cuban National Tidal Service	Cuba
Danish National Space Center	Denmark
Det Dansk Meteorologiske Institute	Denmark
Captainerie du Port de Djibouti	Djibouti
Oceanographic Institute of the Navy	Ecuador
National Institute of Oceanography and Fisheries	Egypt
Finnish Meteorological Institute	Finland
Institut Geographique National, France	France
Service Hyd. et Ocean. de la Marine	France
Dept. of Oceanology and Meteorology, Georgia	Georgia
Bundesamt fur Seeschifffahrt und Hydrographie Hamburg	Germany
Hellenic Navy Hydrographic Service	Greece
Hong Kong Observatory	Hong Kong
Icelandic Coast Guard - Hydrographic Dept.	Iceland
Survey of India	India
National Cartographic Centre of Iran	Iran, Islamic Republic of
Survey of Israel	Israel
ARPAE	Italy
Instituto Talassografico di Trieste	Italy
ISPRA	Italy
University of Ferrara	Italy
Geographical Survey Institute	Japan
Japan Meteorological Agency	Japan
Japan Oceanographic Data Centre, M.S.A.	Japan
National Institute for Polar Research	Japan
National Oceanographic Research Institute	Korea, Republic of
Department of Survey and Mapping	Malaysia
Malta Maritime Authority	Malta
Meteo – France	Martinique
Port Autonome de Nouakchott	Mauritania

Supplier	Country
Meteorological Services, Mauritius	Mauritius
Rijkswaterstaat	Netherlands
Land Information New Zealand (LINZ)	New Zealand
National Institute of Water and Atmospheric Research	New Zealand
Norwegian Mapping Authority	Norway
Hydrographer of The Pakistan Navy	Pakistan
National Mapping and Resource Information Authority	Philippines
Instituto Hidrografico, Lisbon	Portugal
World Data Center B1	Russian Federation
Maritime Port Authority of Singapore	Singapore
Directorate of Hydrography, S.A.	South Africa
Aranzadi	Spain
Dr. Josep Pascual Massaguer	Spain
Geolab	Spain
Instituto Espanol de Oceanografia	Spain
Puertos del Estado	Spain
Swedish Met. and Hyd. Institute	Sweden
Oceanographic Division, Hydrographic Dept.	Thailand
Channel Coastal Observatory	United Kingdom
National Oceanography Centre / Environment Agency	United Kingdom
Port of London Authority	United Kingdom
NOAA / NOS	United States
Panama Canal Commission	United States
University of Hawaii Sea Level Centre (UHSLC)	United States
Oceanographic, Hydrography and Meteorology Service of the Uruguayan Navy (SOHMA)	Uruguay

Annex 3: Selected Papers published 2015-2019

2015

Blunden, J.; Arndt, D.S.; Berry, D.I.; Grist, Jeremy; **Jevrejeva, Svetlana;** Josey, Simon A.; McCarthy, Gerard, Naveria Garabato, Alberto C.; Rayner, Darren; Smeed, David A. 2015. State of the Climate in 2014. *Bulletin of the American Meteorological Society*, 96 (7 (Supplement)). S1-S267. https://doi.org/10.1175/2015BAMSStateoftheClimate.1

Haigh, Ivan D.; Wadey, Matthew P.; Gallop, Shari L; Loehr, Heiko; Nicholls, Robert J.; Horsburgh, Kevin; Brown, Jennifer M.; **Bradshaw, Elizabeth.** 2015. A user-friendly database of coastal flooding in the United Kingdom from 1915–2014. *Scientific Data*, 2. 150021. https://doi.org/10.1038/sdata.2015.21

Wadey, Matthew; Haigh, I.D.; Nicholls , R.J.; Brown, Jennifer; Horsburgh, Kevin; Carroll, B.; Gallop, S.; Mason, T.; **Bradshaw, Elizabeth.** 2015. A comparison of the 31 January–1 February 1953 and 5–6 December 2013 coastal flood events around the UK. *Frontiers in Marine Science*, 2. 84. https://doi.org/10.3389/fmars.2015.00084

Williams, Joanne; Hughes, Chris W.; **Tamisiea, Mark**. 2015. Detecting trends in bottom pressure measured using a tall mooring and altimetry. *Journal of Geophysical Research: Oceans*, 120 (7). 5216-5232. https://doi.org/10.1002/2015JC010955

Woodworth, P.L.; **Hibbert, A**. 2015. Sea-level monitoring in the British Overseas Territories. *Journal of Operational Oceanography*, 8 (2). 123-132. https://doi.org/10.1080/1755876X.2015.1087188

Woodworth, Philip L.; Pugh, David T.; Plater, Andrew J. 2015. Sea-level measurements from tide gauges. In: Shennan, Ian; Long, Antony J.; Horton, Benjamin P. (eds.) *Handbook of Sea-Level Research.* New York, John Wiley & Sons, 557-574, 600pp.

2016

Bradshaw, E.; Woodworth, P.L.; Hibbert, A.; Bradley, L.J.; Pugh, D.T.; Fane, C. and Bingley, R.M. 2016. A century of sea level measurements at Newlyn, SW England. *Marine Geodesy*, 39(2), 115-140, doi:10.1080/01490419.2015.1121175.

Ezer, T.; Haigh, I.D. and **Woodworth, P.L.** 2016. Nonlinear sea-level trends and long-term variability on western European coasts. *Journal of Coastal Research*, 32, 744-755, doi:10.2112/JCOASTRES-D-15-00165.1.

Williams, S.D.P.; Woodworth, P.L. and Hunter, J.R. 2016. Commentary on "Coastal Planning Should Be Based on Proven Sea Level Data" by A. Parker and C.D. Ollier (Ocean & Coastal Management, 124, 1-9, 2016). *Journal of Coastal Research*, 32, 992-997, doi:10.2112/JCOASTRES-D-16A-00005.1.

Woodworth, P.L.; Hunter, J.R.; Marcos, M.; Caldwell, P.; Menéndez, M. and Haigh, I. 2016. Towards a global higher-frequency sea level data set. Submitted to Geoscience Data Journal.

Woodworth, P.L. (ed.) 2016. Manual on Sea-level Measurements and Interpretation, Volume V: Radar Gauges. Paris, Intergovernmental Oceanographic Commission of UNESCO. 104 pp. I*OC Manuals and Guides No.14, vol. V; JCOMM Technical Report No. 89*; (English)

2017

Cartwright, D.E.; **Woodworth, P.L.**; Ray, R.D. 2017. Manuel Johnson's tide record at St. Helena. *History of Geo- and Space Sciences*, 8 (1). 9-19. https://doi.org/10.5194/hgss-8-9-2017

Cipollini, Paolo; Calafat, Francisco M.; **Jevrejeva, Svetlana**; Melet, Angelique; Prandi, Pierre. 2017. Monitoring sea level in the coastal zone with coastal altimetry and tide gauges. *Surveys in Geophysics*, 38 (1). 33-57. https://doi.org/10.1007/s10712-016-9392-0

Hunter, J.R.; **Woodworth, P.L.**; Wahl, T.; Nicholls, R.J. 2017. Using global tide gauge data to validate and improve the representation of extreme sea levels in flood impact studies. *Global and Planetary Change*, 156. 34-45. https://doi.org/10.1016/j.gloplacha.2017.06.007

Jevrejeva, S.; Matthews, A.; Slangen, A. 2017. The Twentieth-Century sea level budget: recent progress and challenges. *Surveys in Geophysics*, 38 (1). 295-307. https://doi.org/10.1007/s10712-016-9405-z

Larson, Kristine M.; Ray, Richard D.; **Williams, Simon D.P.** 2017. A 10-Year Comparison of Water Levels Measured with a Geodetic GPS Receiver versus a Conventional Tide Gauge. *Journal of Atmospheric and Oceanic Technology*, 34 (2). 295-307. https://doi.org/10.1175/JTECH-D-16-0101.1

Marcos, M.; **Woodworth, P**. 2017. Spatiotemporal changes in extreme sea levels along the coasts of the North Atlantic and the Gulf of Mexico. *Journal of Geophysical Research: Oceans*, 122 (9). 7031-7048. https://doi.org/10.1002/2017JC013065

Williams, S.D.P.; Nievinski, F.G. 2017. Tropospheric delays in ground-based GNSS Multipath Reflectometry – experimental evidence from coastal sites. *Journal of Geophysical Research: Solid Earth*, 122 (3). 2310-2327. https://doi.org/10.1002/2016JB013612

Woodworth, P.L. 2017. Differences between mean tide level and mean sea level. *Journal of Geodesy*, 91 (1). 69-90. https://doi.org/10.1007/s00190-016-0938-1

Woodworth, P.L.; Wöppelmann, G.; Marcos, M.; Gravelle, M.; Bingley, R.M. 2017. Why we must tie satellite positioning to tide gauge data. *Eos*, 98 (4), 064037. 13-15. https://doi.org/10.1029/2017EO064037

2018

Filmer, M. S.; Hughes, C. W.; **Woodworth, Philip;** Featherstone, W. E.; Bingham, R. J. 2018. Comparison between geodetic and oceanographic approaches to estimate mean dynamic topography for vertical datum unification: evaluation at Australian tide gauges. *Journal of Geodesy*. 28, pp. https://doi.org/10.1007/s00190-018-1131-5

Frederikse, Thomas; **Jevrejeva, Svetlana;** Riva, Riccardo E.M.; Dangendorf, Sönke. 2018. A consistent sea-level reconstruction and its budget on basin and global scales over 1958–2014. *Journal of Climate,* 31 (3). 1267-1280. https://doi.org/10.1175/JCLI-D-17-0502.1

Kendon, Mike; McCarthy, Mark; **Jevrejeva, Svetlana; Matthews, Andrew;** Legg, Tim. 2018. State of the UK climate 2017. *International Journal of Climatology*, 38. 1-35. https://doi.org/10.1002/joc.5798

Rickards, L. 2018. Comments on the Paper "Is the Sea Level Stable at Aden, Yemen?" by Albert Parker and Clifford D. Ollier in *Earth Systems and Environment* (Volume 1, December 2017). Earth Syst Environ Vol 2: No 1. https://doi.org/10.1007/s41748-018-0036-z

Woodworth, P.L. 2018. Sea level change in Great Britain between 1859 and the present. *Geophysical Journal International*, 213 (1). 222-236. https://doi.org/10.1093/gji/ggx538

Woodworth, Philip L.; Hibbert, Angela. 2018. The nodal dependence of long-period ocean tides in the Drake Passage. *Ocean Science,* 14 (4). 711-730. https://doi.org/10.5194/os-14-711-2018

Woodworth, Philip L.; Rowe, Glen H. 2018. The tidal measurements of James Cook during the voyage of the Endeavour. *History of Geo- and Space Sciences*, 9 (1). 85-103. https://doi.org/10.5194/hgss-9-85-2018

2019

Aarup, T.; Wöppelmann, G.; **Woodworth, P.L.;** Hernandez, F.; Vanhoorne, B.; Schöne, T.; Thompson, P.R. 2019. Comments on the article "Uncertainty and bias in electronic tide-gauge records: Evidence from collocated sensors" by Stella Pytharouli, Spyros Chaikalis, Stathis C. Stiros in Measurement (Volume 125, September 2018). *Measurement*, 135. 613-616. https://doi.org/10.1016/j.measurement.2018.12.007

Marcos, Marta; Wöppelmann, Guy; **Matthews, Andrew;** Ponte, Rui M.; Birol, Florence; Ardhuin, Fabrice; Coco, Giovanni; Santamaría-Gómez, Alvaro; Ballu, Valerie; Testut, Laurent; Chambers, Don; Stopa, Justin E. 2019. Coastal Sea Level and Related Fields from Existing Observing Systems. *Surveys in Geophysics*. https://doi.org/10.1007/s10712-019-09513-3

Qu, Ying; **Jevrejeva, Svetlana;** Jackson, Luke P.; Moore, John C. 2019. Coastal Sea level rise around the China Seas. *Global and Planetary Change*, 172. 454-463. https://doi.org/10.1016/j.gloplacha.2018.11.005

Williams, Joanne; **Matthews, Andrew; Jevrejeva, Svetlana**. 2019. Development of an automatic tide gauge processing system. Southampton, National Oceanography Centre, 26pp. *National Oceanography Centre Research and Consultancy Report,* 64

Woodworth, Philip L. 2019. The global distribution of the M1 ocean tide. *Ocean Science,* 15 (2). 431-442. https://doi.org/10.5194/os-15-431-2019

Annex 4: Acronyms

ACRE	Atmospheric Circulation Reconstructions over the Earth
BODC	British Oceanographic Data Centre
CME	Commonwealth Marine Economies
DOI	Digital Object Identifier
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
EPSG	European Petroleum Survey Group
GCN	GLOSS Core Network
GESLA	Global Extreme Sea Level Analysis
GGOS	Global Geodetic Observing System
GLOSS	Global Sea Level Observing System
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
IAG	International Association of Geodesy
IAPSO	International Association for the Physical Sciences of the Oceans
ICSU-WDS	International Science Council – World Data System
IGS	International GNSS Service
IOC	Intergovernmental Oceanographic Commission
IOTWS	Indian Ocean Tsunami Warning System
IPCC	Intergovernmental Panel on Climate Change
ISC	International Science Council (formerly ICSU)
ISO	International Standards Organisation
IUGG	International Union of Geodesy and Geophysics
JCR	Journal Citation Reports
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
MSL	Mean Sea Level
MTL	Mean Tide Level
NERC	Natural Environment Research Council
netCDF	Network Common Data Form
NOC	National Oceanography Centre, UK
ODINAfrica	Ocean Data and Information Network for Africa
PNAS	Proceedings of the National Academy of Sciences of the USA
PSMSL	Permanent Service for Mean Sea Level
RDA	Research Data Alliance
RLR	Revised Local Reference
SONEL	Système d'Observation du Niveau des Eaux Littorales
TIGA	IGS Working Group Tide Gauge Benchmark Monitoring Project