Report by the Permanent Service for Mean Sea Level (PSMSL) for the Period 2011-2015 to the XXVI General Assembly of the IUGG, Prague, Czech Republic, June/July 2015

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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 hosted by the National Oceanography Centre (NOC), Liverpool with funding provided by the UK Natural Environment Research Council. PSMSL operates under the auspices of the International Council for Science (ICSU).

The PSMSL was established in 1933 by Joseph Proudman who became its first Secretary. Thus 2013 marked the 80th anniversary of the founding of PSMSL. To celebrate this milestone, PSMSL organised or co-organised three meetings: a workshop in Liverpool, UK, on major research topics in sea level science, including talks reviewing aspects of the IPCC Fifth Assessment Report (Working Group I); a symposium entitled "Implications of sea level change for the coastal zone - A symposium to mark the 80th anniversary of the Permanent Service for Mean Sea Level (PSMSL)" at the IAHS/IAPSO/IASPEI Joint Assembly in Gothenburg, Sweden; and a session at EGU 2013**:** Global and regional sea level rise and variability: from past to future.

The primary aim of the PSMSL is providing 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 4 years over 10000 station-years of data were entered into the PSMSL database, increasing the total PSMSL data holdings to over 65000 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 (GLOSS) core network.

New products have been made available over the last four years including trend maps and associated uncertainty values; links with the Système d'Observation du Niveau des Eaux Littorales (SONEL) have been further developed to facilitate distribution of additional geodetic data; and data from *in situ* ocean bottom pressure (OBP) recorders from all possible sources is being made available through PSMSL. PSMSL has also taken the lead in data archaeology through GLOSS.

PSMSL staff have continued to be active in a variety of international meetings, working groups, conferences and workshops including IOC GE-GLOSS and IOC Coordination Groups for tsunami warning systems, IPCC, GGOS, WDS, WCRP, and EGU over the last 4 years. In addition, they have 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.

Activities

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 also provides a wider Service to the sea level community. Established in 1933, the PSMSL continues to be responsible for the collection, publication, analysis and interpretation of sea level data. PSMSL is hosted by the National Oceanography Centre (NOC), Liverpool with funding provided by the UK Natural Environment Research Council. The PSMSL operates under the auspices of the International Council for Sciences (ICSU) and is one of the main data centres for both the International Association for the Physical Sciences of the Oceans (IAPSO) and the International Association of Geodesy (IAG). It also has links with the Global Geodetic Observing System (GGOS). The PSMSL continues to work closely with other members of the sea level community through the Intergovernmental Oceanographic Commission's Global Sea Level Observing System (GLOSS). The PSMSL is applying for membership of the new ICSU World Data System (WDS) and has completed the IAG Service Assessment Questionnaire.

The data set and ancillary information are provided free of charge and are made available to the international scientific community through the PSMSL website. The metadata includes descriptions of benchmarks and their locations, types of instrumentation and frequency of data collection (where available) as well as notes on other issues that we feel the users should be aware of (e.g. earthquakes that are known to have occurred in the vicinity or subsidence due to local groundwater extraction). The free access to data by users is central to the PSMSL's mission, and conversely no supplier is ever paid for their data, nor are licensing terms ever entered into.

2. Staffing and funding

Dr. Lesley Rickards continues to act as the Director of the PSMSL. The main PSMSL scientific staff concerned with the collection and analysis of monthly mean sea level data over the period have been Prof. Philip Woodworth, Dr. Simon Holgate, Dr. Svetlana Jevrejeva and Dr. Mark Tamisiea. Ms. Kathy Gordon continues to be responsible for management of the mean sea level data set and Dr. Andrew Matthews has worked on re-structuring the database, improving data delivery and providing new tools to aid data input, quality control and reporting. 2012 saw the departure of Dr. Simon Holgate, who we thank for all of his contributions over the previous 10 years. And we welcome Dr. Simon Williams, already a well-established scientist within NOC, to the PSMSL scientific staff.

Alongside the monthly mean sea level data collection, the PSMSL, together with BODC, is responsible for an archive of delayed-mode higher-frequency sea level data from the GLOSS network. This activity has so far included Miss Elizabeth Bradshaw and other colleagues in the British Oceanographic Data Centre (BODC).

Funding continues to be provided by the UK Natural Environment Research Council (NERC, the parent body of NOC). The document prepared in 2010 by PSMSL for NERC as part of its review of National Capability to aid future funding decisions resulted in PSMSL being one of the two areas in NOC given a high rating enabling us to continue to operate at the same level of funding. The document highlighted PSMSL's unique role and the synergy generated by its co-location with NOC.

3. PSMSL-related scientific meetings, activities and events

PSMSL staff have continued to be active participants in the IOC Group of Experts on the Global Sea Level Observing System (GLOSS) and GGOS meetings, co-convened sea level sessions at the EGU and contributed to IOC coordination group tsunami warning system meetings. PSMSL has also contributed to the IPCC Fifth Assessment Report with Dr Svetlana Jevrejeva a lead author for Working Group I, Prof. Philip Woodworth a review editor and other PSMSL staff also contributing.

2013 marked the 80th anniversary of the foundation of the PSMSL. To commemorate this PSMSL hosted or co-convened the following events:

- A workshop in Liverpool, UK (October 2013), on major research topics in sea level science. The workshop included talks reviewing aspects of the IPCC Fifth Assessment Report (Working Group I). There were also presentations covering many aspects of regional variability in sea level.
- A symposium entitled "Implications of sea level change for the coastal zone - A symposium to mark the 80th anniversary of the Permanent Service for Mean Sea Level (PSMSL)" at the IAHS/IAPSO/IASPEI Joint Assembly in Gothenburg, Sweden (July 2013).
- A session at EGU 2013**:** Global and regional sea level rise and variability: from past to future.

In 2014 Dr Svetlana Jevrejeva co-organised a Summer school "Sea-level change: Observations and processes" in Delft, the Netherlands, attended by 37 students. She, together with Prof Philip Woodworth, gave lectures about tide gauge observations, PSMSL, GLOSS activities, PSMSL data sets, and data archaeology. In addition, a short demonstration of the data access at the PSMSL webpage, link to the SONEL data sets, link to the IOC manuals, and training material were given. In addition, Prof. Philip Woodworth and Dr. Simon Holgate were lecturers on the GLOSS training course held in Bangkok.

Dr. Lesley Rickards is a member of the ICSU World Data System Scientific Committee and chairs the sub-committee on Membership and Accreditation.

4. Collection, analysis, publication and interpretation of monthly and annual means of sea level from the global network of tide gauges

Currently, the PSMSL data bank for monthly and annual sea level data holds over 65,000 station-years of data from over 2200 stations. Data from each site are carefully quality controlled and, wherever possible, reduced to a common datum, whose stability is monitored through a network of geodetic benchmarks. Figure 1a indicates the number of station years added to the database each year and Figure 1b shows the number of stations. An average of approximately 2650 station years were added per year, with an exceptionally high number (4222) in 2013. This was due in part to an effort to chase up as much data as possible prior to the Group of Experts on GLOSS meeting towards the end of 2013, and also due to receiving a backlog of data from the new network in Spain. The number of stations updated has varied between 643 (2011) to 786 (2013). During the period 2011 to 2014, 1038 stations have been updated as shown in Figure 2. It can be seen that while many regions have supplied data (e.g. North America, Europe, Japan, Australia, New Zealand, South Africa, India), there are still gaps in the Arctic and Antarctic, and parts of South America and Africa.

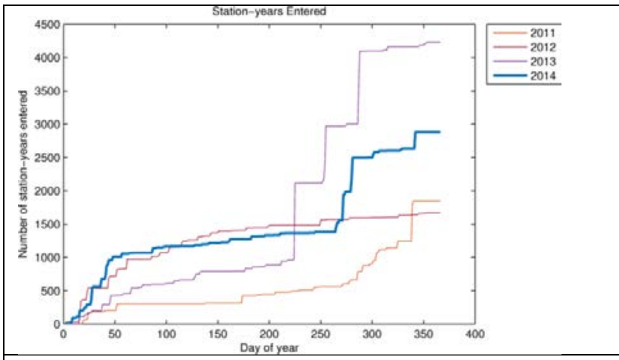


Figure 1a: Number of station years added to PSMSL database between 2011 and 2014

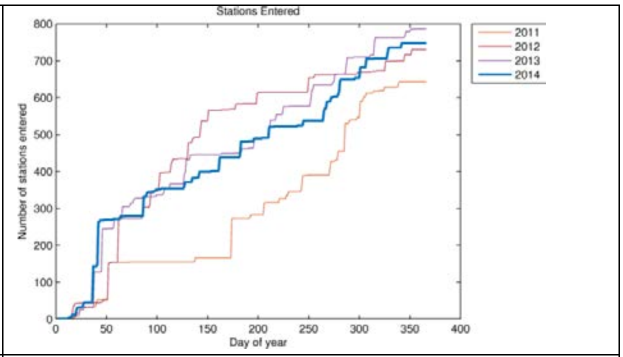


Figure 1b: Number of stations with data added to PSMSL database 2011 to 2014

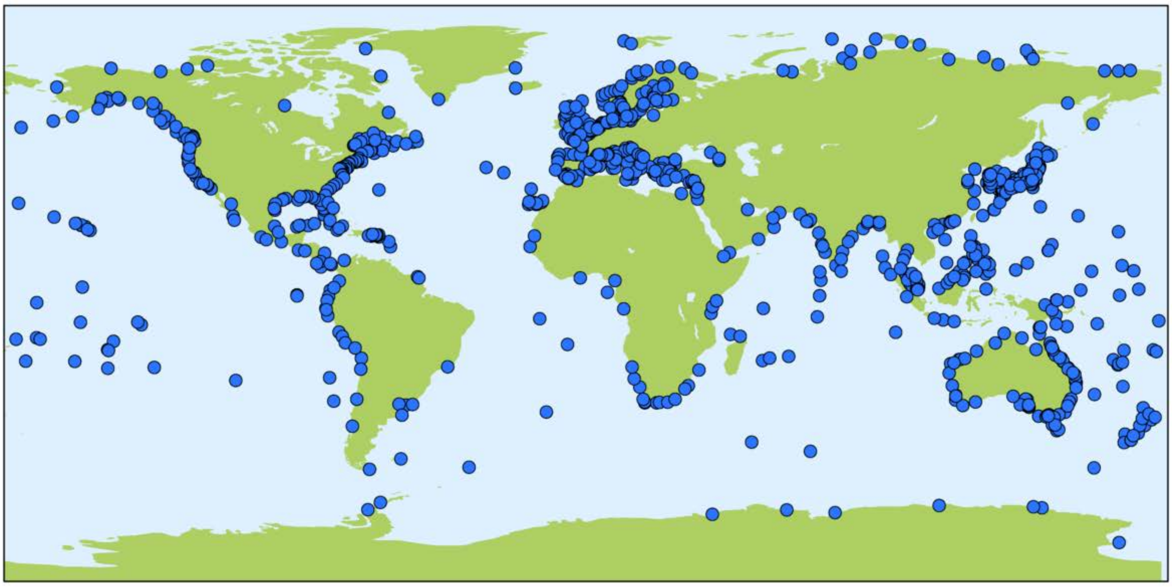


Figure 2: New PSMSL data received between 2011 and 2014

Figure 3 gives a more detailed view of the data held by PSMSL, indicating where data had been supplied in the past – in particular the decline in the number of stations in the Arctic is noticeable. 777 stations have provided data from 2013 or after with a further 196 providing data from 2010-2012. These (973 stations) can all be considered as active stations, but there are 987 stations for which no data have been supplied since before 1995. Some of these have undoubtedly ceased to operate; for others contact with the operators is being pursued. New stations are also coming on line providing near-real-time data for tsunami monitoring, but many of these do not yet supply the quality controlled mean sea level values to the PSMSL. There continue to be gaps in data receipts from parts of SE Asia, central and South America; these are presently being targeted to try to improve data flow. Africa continues to receive special attention through ODINAfrica and the Indian Ocean Tsunami Warning System (IOTWS). Although data flow has improved considerably over the last decade some of the gauges require a higher level of maintenance. Close links have been maintained with the University of Hawaii Sea Level Center and other international sea level data centres.

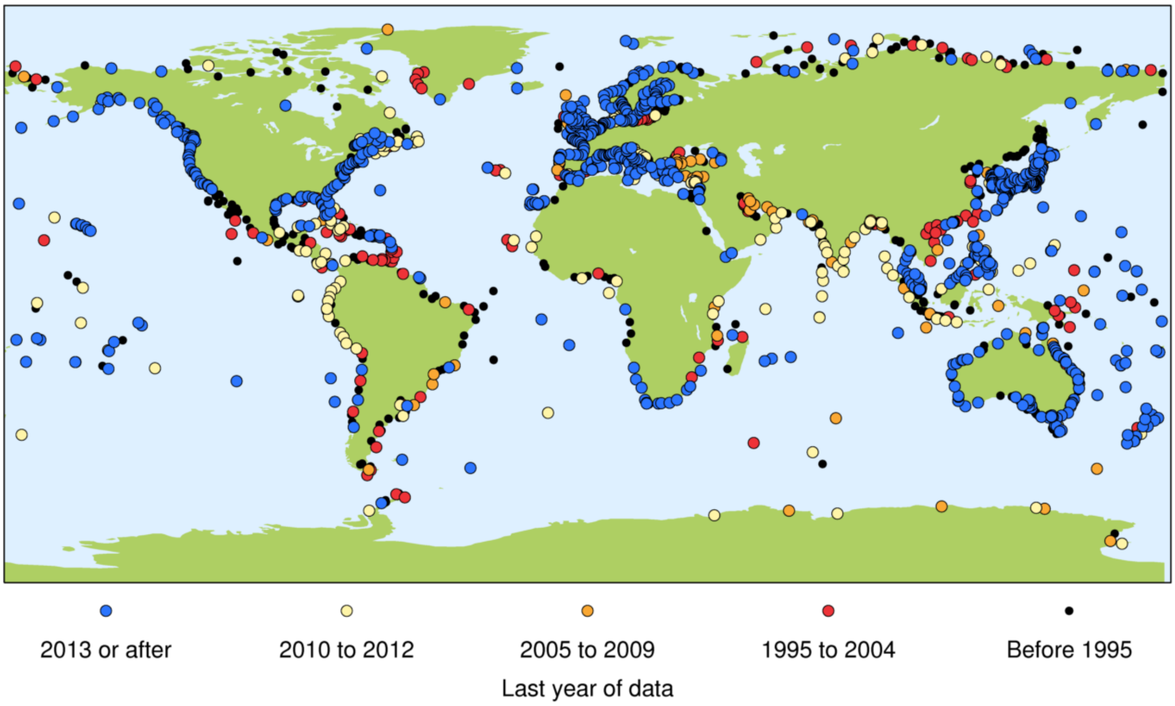


Figure 3: Year of most recent data received by PSMSL

4.1 Interactive map showing long-term trends

The relative sea level trends map allows interactive investigation of global mean sea level trends since 1900. This is updated annually to include new data, so the latest version includes data received in 2014. The limits of the period to be viewed can be selected by either moving the buttons on the slider or by entering the values in the two text boxes. A period of at least thirty years must be selected. The map will display the annual sea level trend at each station that has suitable data available over the selected period. Since its first introduction the trends map has been improved by the addition of uncertainty estimates: the pop-up boxes for each tide gauge shown on the trends map now include an uncertainty. Both the estimated trend and the uncertainty will change as the time span chosen is changed. In order to calculate these results, the methodology used has changed. Further information is available on the methods page (see: http://www.psmsl.org/products/trends/methods.php).

Note that these measured trends are not corrected for local land movement. Furthermore, no attempt has been made to assess the validity of any individual fit, so results should not be treated as a publication quality values suitable for use in planning or policy making.

The map should be used with some care as anomalous trends have many causes:

- land movements (e.g. earthquakes, glacial isostatic adjustment)
- unexplained instrumental datum shifts
- changes in atmospheric pressure
- short records

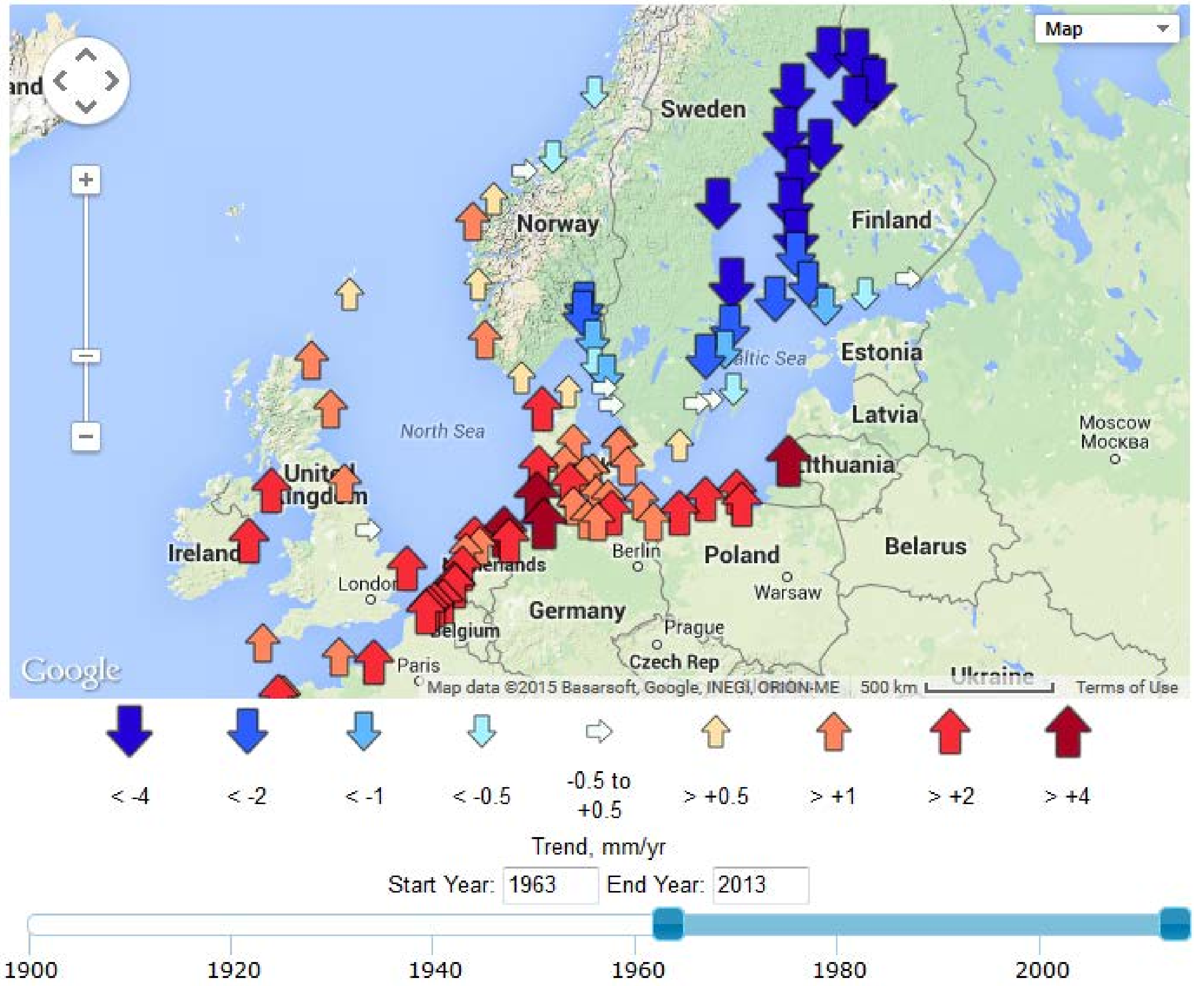
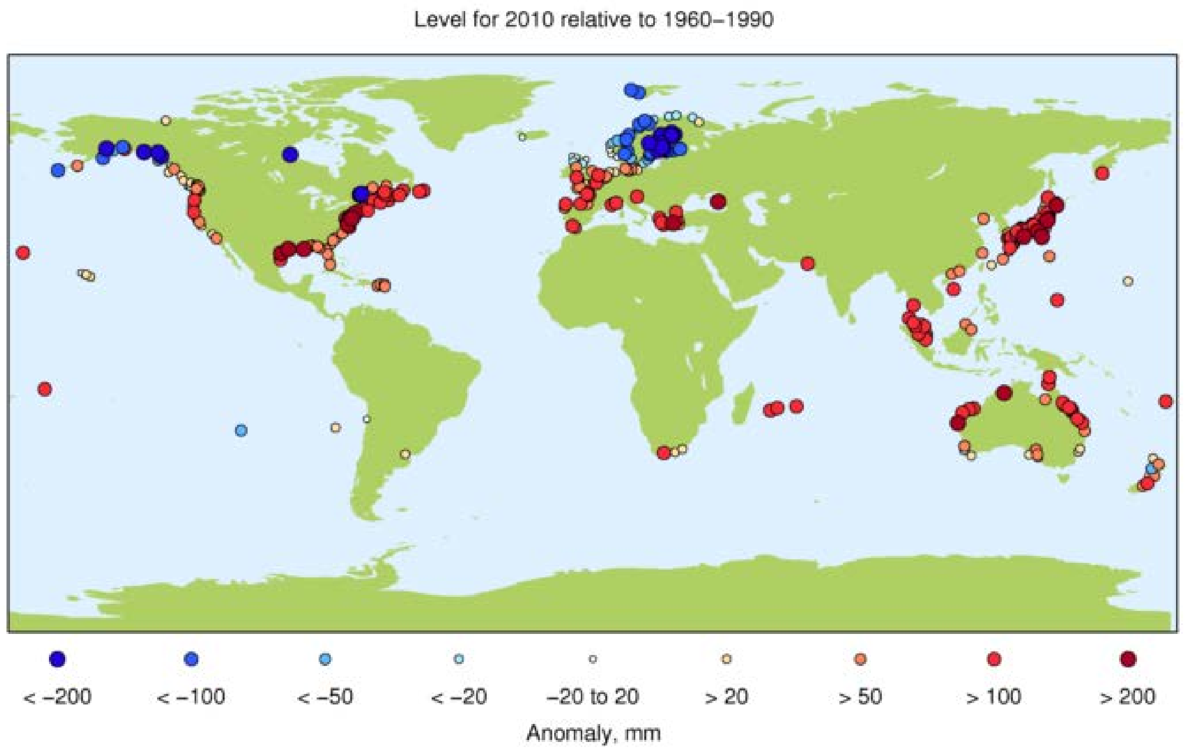


Figure 4: Sample map showing relative sea level trends

4.2 Interactive map showing sea level anomalies

Annual mean sea level can vary considerably from year to year in response to various meteorological and oceanographic forcings, typically by hundreds of millimetres. This product allows one to examine the global variations in a year of your choice: select this year using either the slider or the text box. The map presents the difference between the annual RLR data for each station (which is quality and datum controlled) compared to that station's long term mean over the baseline period of 1960-1990.

The long term trend at each station (estimated using the baseline period) can be removed if required. This will prevent results being dominated by long term changes, but will result in the loss of stations for which there is not enough data to calculate a trend. Further information is provided on the methods and derived trends pages of the PSMSL web-site.



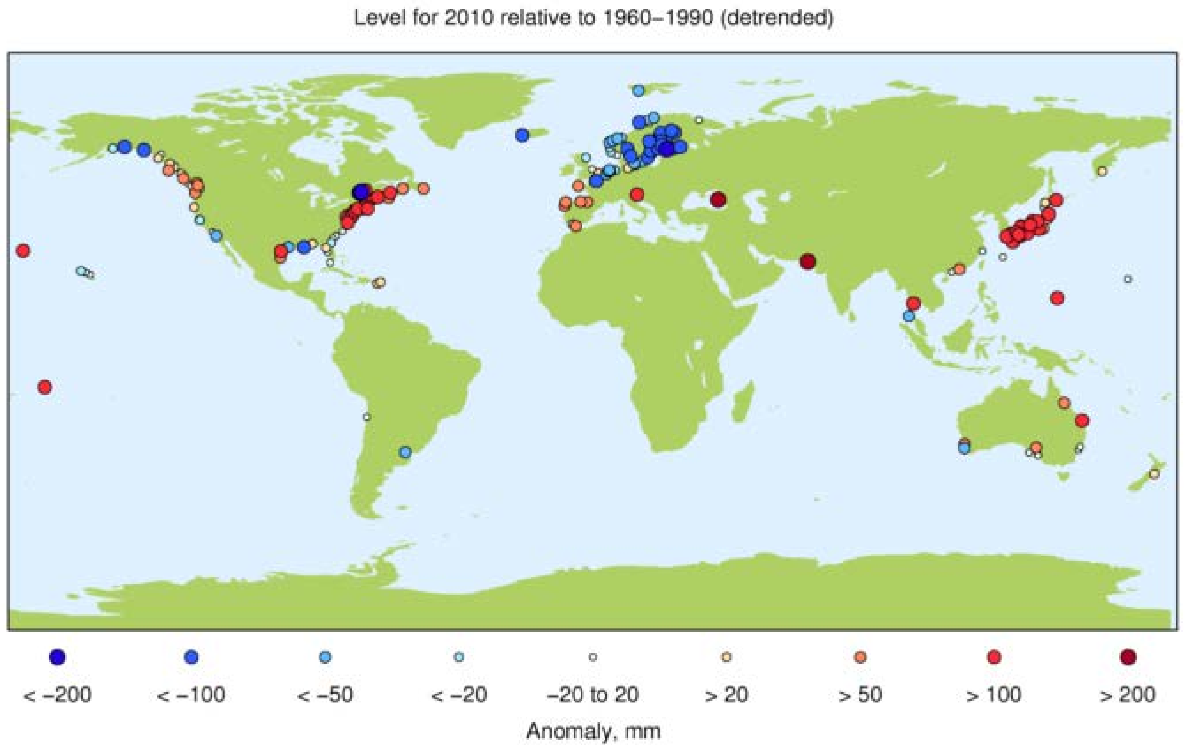


Figure 5: Sea level anomalies for 2010 relative to 1960-1990. (Top image: not detrended. Bottom image: detrended)

4.3 Land Motion at Tide Gauges: Collaboration with SONEL

PSMSL has been working with Système d'Observation du Niveau des Eaux Littorales (SONEL, http://www.sonel.org/) to facilitate distribution of additional geodetic data. SONEL is the data centre for the IAG TIGA working group, as well as a data assembly centre for the GLOSS network. Along with links to data at the other GLOSS centres, PSMSL has implemented links to the SONEL website in cases where there is GNSS data within 10 km of a tide gauge. SONEL also has used the tide gauge trends derived by the PSMSL to create a map of relative vs. absolute sea level trends on their website. It should be noted that until a TIGA combined solution exits, we are using the ULR5 solution. SONEL has also collected data where levelling ties exist between the GNSS receivers and the tide gauge. This information allows one to reference the PSMSL RLR tide gauge time series to an ITRF ellipsoidal height. PSMSL is working with SONEL to distribute this information on the PSMSL website in the near future.

5. Collection of delayed-mode higher-frequency data from GLOSS Core Network sea level measuring stations

The PSMSL together with BODC is responsible for an archive of delayed-mode higher frequency sea level data (e.g. hourly or more frequent values) from the GLOSS network of 290 stations. This activity builds on the earlier work carried out as the Delayed-mode Sea Level Data Assembly Centre (DAC) for the World Ocean Circulation Experiment (WOCE). Between August 2011 and May 2015, new data have been received from Australia, Brazil, Canada, Germany, Iceland, Japan, Korea, UK and USA (NOAA and UHSLC). Further data from UK GLOSS sites have been digitized from the original charts to fill in some gaps in the historical record. These are being added to the high-frequency delayed-mode databank. In addition, data up to the end of 2014 from the gauges that are part of the ODINAfrica and Indian Ocean network have been downloaded, processed and quality controlled, although not all of the gauges have been operational for the entire period. The data (both 1 minute and 15 minute) are available on the GLOSS web-site.

6. Data Archaeology in collaboration with GLOSS

Many historical tide gauge data still exist in non-digital form. These mostly paper-based data sets 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 2001, PSMSL, together with BODC and University of Hawaii Sea Level Center (UHSLC), initiated a GLOSS data archaeology and rescue project. This resulted in the digitising and quality control of paper records from nearly 100 tide gauges, extending the digital record by over 1400 years of hourly data. This data archaeology effort has been reinvigorated in 2012 with a questionnaire to all GLOSS contacts, which has identified a vast amount of non-digital historical tide gauge measurements, augmenting the large volume already catalogued, for example, in France and the U.K. Amongst existing projects, BODC is currently scanning and digitising analogue chart and manuscript sea-level records, some of which date back to 1853.

A GLOSS data archaeology 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. In the future, coordination of a tide gauge data rescue project with the Atmospheric Circulation Reconstructions over the Earth (ACRE) programme (carrying out rescue of air pressure data) could result in interesting synergies. To date several GLOSS members have developed software to automatically digitise analogue records on charts which were reported to the 13th meeting of the GLOSS Group of Experts. As a result GLOSS will create a repository of software for scanning analogue charts.

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.

7. Technology development – radar gauges

With some funding provided by the IOC GLOSS Technical Secretary, PSMSL and colleagues from the NOC Ocean Engineering and Technology Group undertook two pieces of work. These were (i) to develop and design a second generation sea level measuring station system that requires limited operator intervention and (ii) development of a facility and methodology for calibration of offsets in the measured range of the radar and for estimation of radar range accuracy, obviating the need for local operators to make dipping measurements.

It had been agreed that it would be beneficial to construct a second generation ODINAfrica gauge which would be more reliable, less power hungry and require less maintenance. In addition, a system that does not use pressure sensors (i.e. a radar gauge) would last longer without maintenance visits and a more robust (corrosion-proof) satellite antenna would greatly help reliability. Various different loggers and tide gauges were considered to meet the requirements outlined above (e.g. Waterlog DCP, OTT RLS, Vega, DAA, etc.). Battery replacement would still be an issue, but this is considered the sort of minimal maintenance that can be carried out locally. Two Waterlog DCP loggers were supplied to PSMSL by IOC, together with two OTT RLS radar sensors and component parts, which were assembled to provide two complete tide gauge systems. The new systems are contained within two separate cabinets instead of the one cabinet used in the existing ODINAfrica installations. This allows a much larger rechargeable battery to fitted, thus extending the operational life between servicing. This is something that had been a serious issue with the previous ODINAfrica equipment. In addition, alternative battery chargers have been fitted that extend the charging life-time of the battery. These two complete tide gauge systems have been tested and are ready to be deployed in Africa or the Indian Ocean once a suitable location has been agreed.

Radar gauges generally perform well and are stable, but the determination of their datum has been addressed in the field with the use of complementary measurements with a tide pole, or by dipping measurements in an adjacent stilling well where one exists. However, this has never been a satisfactory situation, and enthusiasm by local operators to make regular tide pole or dipping measurements has never been high. This, together with the availability of a new generation of sensors (in particular the DAA 3611i), has provided motivation for developing a calibration facility.

Measurements were first made in the field, rather than in the laboratory. Three radar gauges (DAA 3611i, OTT RLS and the Vega VegaPuls61) were installed at the Holyhead tide gauge station in Wales, UK. The resulting data was then used to evaluate their performance against the existing onsite reference gauge, the Tide Gauge Inspectorate Bubbler system. The results of the tests with the real sea surface and with the stirrup were consistent. They showed that the DAA 3611i unit performed exceptionally well showing a mean difference (i.e. difference from its nominal reference mark) of approximately 2 mm. Subsequently, an additional testing phase was carried out at the NOC Liverpool facility to check if the above 'real world' figures could be repeated in a laboratory environment. The tests consisted of two sections, one utilising the previously used metal plate as the target and the other, a small water pool. Multiple measurements were made for each sensor, varying the range distance between the sensor and the targets. Overall the RLS and DAA radar gauges agree with the results from the 'real world' experiments. The DAA seemed to mirror the findings in all tests to a very high degree (to within 2 mm).

8. Ocean Bottom Pressure Records

With a recent grant from the UK Natural Environment Research Council, the PSMSL is working to provide data from *in situ* ocean bottom pressure (OBP) recorders from all possible sources, a remit given to the PSMSL by IAPSO in 1999. The aim is to provide consistently-processed bottom pressure records with hourly and daily sampling for use in tidal, oceanographic and geophysical research. Typically, the original data sets are not distributed to avoid duplication with existing repositories. The processing procedures, described on the web-site, provide estimates of tidal signal and the instrumental drift for each deployment. The page on file formats describes the data provided in the hourly and daily data files.

Currently, a limited set of data is available; this will continue to grow with time. The map below shows the 66 sites for which data are currently available. This initial release contains data from the National Oceanography Centre's Drake Passage deployments, ten tsunameters archived at the US National Data Buoy Center, and a collection of records from the north-east Atlantic provided by Prof. Wendell S. Brown. Effort has focused on longer records (a year or more) and frequently occupied locations. The best record in this respect is the NOC's 19-year-long record at a southern location in the Drake Passage. However, the data provided by Prof. Brown illustrates another important aspect of the effort: improving the availability of historic data. While most of the records in this data set are short in length, they previously had not been easily available. Not all of the historical data collected by the NOC is included, but details are provided on the web-site of how to obtain those additional OBP records.

Figure 6: Location of Ocean Bottom Pressure Recorder data available from PSMSL

9. Publications

Selected recent papers published by NOC scientists partially supported by the PSMSL are listed in Annex 1. These address global sea-level rise and regional changes, as well as dynamic ocean topography. Perhaps the most notable, in terms of high-level quality control, is the paper by Woodworth et al., "Towards worldwide height system unification using ocean information". The work on this paper and the continuing research has led to a systematic review of the datum information at the studied tide-gauge sites.

One further paper that merits inclusion is an updated overview of PSMSL and its data sets. This paper replaces the previous overview by Woodworth and Player (2003) and is now the definitive article for citation of the PSMSL data set:

Holgate, S.J; Matthews, A.; Woodworth, P.L.; Rickards, L.J.; Tamisiea, M.E.; Bradshaw, E.; Foden, P.R.; Gordon, K.M.; Jevrejeva, S. & Pugh, J., "New Data Systems and Products at the Permanent Service for Mean Sea Level" *Journal of Coastal Research,* 2013, Volume 29, Issue 3: pp. 493 – 504. doi: http://dx.doi.org/10.2112/JCOASTRES-D-12-00175.1

In order to assess the wider usage of the PSMSL data set, a search of the scientific literature for the years between 2011 and 2014 was carried out. The result is that approximately 60 papers have been published per year which have used the PSMSL data set.

10. Summary and forward look

It can be seen that the last four years have been a further active period with regard to important workshops and conferences, and a busy one with regard to data acquisition and analysis. The functions provided by the PSMSL are in as much demand as ever, and several successful events were organised to celebrate the 80th anniversary of the Service in 2013. In addition new products continue to be developed and activities have expanded to include provision of data from *in situ* ocean bottom pressure (OBP) recorders.
Future plans include:

- Improved integration of the mean sea level data set with higher frequency data and improving the quality of accompanying metadata;
- 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;
- Continue collaboration with SONEL (IAG TIGA Working Group data centre) and with GGOS;
- Expansion of bottom pressure record section and data;
- Further develop data archaeology with the Group of Experts on GLOSS;
- Redevelopment of capacity building/training material.

Particular thanks as usual go to PSMSL staff and to colleagues at the National Oceanography Centre and British Oceanographic Data Centre who contribute part of their time to PSMSL activities.

Annex 1: Selected Papers

Bos, M. S.; **Williams, S. D. P.**; Araujo, I. B. & Bastos, L. "The effect of temporal correlated noise on the sea level rate and acceleration uncertainty.", *Geophysical Journal International*, 2014, **196**, 1423-1430.

Gehrels, W. R. & **Woodworth, P. L.**, "When did modern rates of sea-level rise start?", *Global and Planetary Change*, 2013, **100**, 263-277.

Henry, O.; Prandi, P.; Llovel, W.; Cazenave, A.; **Jevrejeva, S.**; Stammer, D.; Meyssignac, B. & Koldunov, N., "Tide gauge-based sea level variations since 1950 along the Norwegian and Russian coasts of the Arctic Ocean: Contribution of the steric and mass components", *Journal of Geophysical Research-Oceans*, 2012, **117**, C06023.

Jevrejeva, S.; Moore, J.; Grinsted, A.; Matthews, A. & Spada, G. "Trends and acceleration in global and regional sea levels since 1807", *Global and Planetary Change*, 2014, **113**, 11-22.

Long, A.; Barlow, N.; Gehrels, W.; Saher, M.; **Woodworth, P.**; Scaife, R.; Brain, M. & Cahill, N. "Contrasting records of sea-level change in the eastern and western North Atlantic during the last 300 years". *Earth and Planetary Science Letters*, 2014, **388**, 110-122.

Perez, B.; Payo, A.; Lopez, D.; **Woodworth, P. L.** & Alvarez Fanjul, E. "Overlapping sea level time series measured using different technologies: an example from the REDMAR Spanish network", *Natural Hazards and Earth System Sciences*, 2014, **14**, 589-610.

Rickards, L., Matthews, A., Gordon, K., Tamisiea, M., Jevrejeva, S., Woodworth, P. and Bradshaw, E. 2014. Celebrating 80 years of the Permanent Service for Mean Sea Level (PSMSL). pp.11-15 in, Complex Interfaces Under Change: Sea-River-Groundwater-Lake. International Association of Hydrological Sciences, Publication 365, Proceedings of HP2/HP3, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013. (eds. C. Cudennec, M. Kravchishina, J. Lewandowski, D. Rosbjerg & P. Woodworth). ISBN 978-1-907161-43-8. pp, 100 + viii.

Tamisiea, M. E.; Hughes, C.; **Williams, S. D. P.** & Bingley, R. M. "Sea level: measuring the bounding surfaces of the ocean.", *Philosophical Transactions of the Royal Society A-Mathematical Physical and Engineering Sciences*, 2014, **372**

Woodworth, P.; Hughes, C.; Bingham, R. & Gruber, T., "Towards worldwide height system unification using ocean information", *Journal of Geodetic Science*, 2012, **2**, 302-318.

Woodworth, P. L.; Foden, P. R.; Jones, D. S.; Pugh, J.; **Holgate, S. J.**; Hibbert, A.; Blackman, D. L.; Bellingham, C. R.; Roussenov, V. M. & Williams, R. G., "Sea level changes at Ascension Island in the last half century" *African Journal of Marine Science*, 2012, **34**, 443-452.

Woodworth, P. L.; Maqueda, M. Ã. M.; Roussenov, V. M.; Williams, R. G. & Hughes, C. W. "Mean sea-level variability along the northeast American Atlantic coast and the roles of the wind and the overturning circulation", *Journal of Geophysical Research: Oceans*, 2014,