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Source: Journal of Coastal Research, 29(3) : 493-504

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-12-00175.1

Journal of Coastal Research	29	3	493–504	Coconut Creek, Florida	May 2013

New Data Systems and Products at the Permanent Service for Mean Sea Level

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ABSTRACT

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Sea-level rise remains one of the most pressing societal concerns relating to climate change. A significant proportion of the global population, including many of the world's large cities, are located close to the coast in potentially vulnerable regions such as river deltas. The Permanent Service for Mean Sea Level (PSMSL) continues to evolve and provide global coastal sea-level information and products that help to develop our understanding of sea-level and land motion processes. Its work aids a range of scientific research, not only in long-term change, but also in the measurement and understanding of higher frequency variability such as storm surges and tsunamis. The PSMSL has changed considerably over the past 10 years, and the aim of this paper is to update the community about these changes as well as provide an overview of our continuing work.

ADDITIONAL INDEX WORDS: *Tide gauges, climate change, vertical land movements, ocean circulation, geodesy.*

INTRODUCTION

The Permanent Service for Mean Sea Level (PSMSL) is one of the oldest geophysical data services. Even with this long history, the PSMSL continues to see many changes and is rapidly evolving to meet the needs of our community.

Founded in 1933, at the Liverpool Tidal Institute, under the guidance of Joseph Proudman, the PSMSL is the global data bank for long-term sea-level information from tide gauges. The PSMSL celebrated its 75th Anniversary in 2008 with a dedicated sea-level session at the European Geosciences Union meeting in Vienna, cosponsorship of the William Smith meeting at the Geological Society in London, and a session at the British Association "Festival of Science," held that year in Liverpool. These meetings illustrate the breadth of the work that the PSMSL covers. On the one hand, the PSMSL's data set is used for research across a wide range of geophysical disciplines (including oceanography, geology, geodesy, and climate change) by a large, international community of sea-level scientists (*e.g*., see Church *et al*., 2010). On the other hand, the PSMSL provides a much wider service to the community than simply being a data bank. It acts as a focus of knowledge and expertise on sea-level measurement techniques and a provider of technical and scientific outreach information to coastal stakeholders and the general public. The PSMSL scientists have participated in each of the Intergovernmental Panel on Climate Change assessment reports and continue to be actively involved in the current process. The PSMSL was also heavily involved in the World Climate Research Programme production of an important book on sea-level rise and variability (Church *et al*., 2010).

During 2010 the PSMSL launched its new website with a dedicated domain. Now found at http://www.psmsl.org, the website is home to a redesigned data delivery system and a number of new products, which will be described below. One product of particular relevance to this paper, however, is that in addition to weekly data updates, the PSMSL now produces an annual release. All the data and figures in this paper refer to the 2011 data release dated January 25, 2012. These data can be downloaded from http://www.psmsl.org/data/obtaining/year_end/2011/.

Despite the many changes, the PSMSL continues, as it has from its inception, to be 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). The PSMSL operates under the auspices of the International Council for Science (ICSU) and reports formally to IAPSO's Commission on Mean Sea Level and Tides (for a list

DOI: 10.2112/JCOASTRES-D-12-00175.1 received 5 September 2012; accepted in revision 2 October 2012; corrected proofs received 27 November 2012.
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Published Pre-print online 18 December 2012.

Table 1. *Abbreviation explanations*.

Abbreviation	Explanation	Organization location
BGAN	Broadband Global Area Network	product of Immarsat, in London, U.K.
BODC	British Oceanographic Data Centre	Liverpool, U.K.
GCOS	Global Climate Observing System	joint program of the World Meteorological Organization (IOC), the United Nations Environment Programme, and ICSU
GGOS	Global Geodetic Observing System	program of IAG
GIA	glacial isostatic adjustment	—
GLOSS	Global Sea Level Observing System	program of IOC, Paris, France
GNSS	Global Navigation Satellite Systems	
GOES	Geostationary Operations Environmental Satellites	National Oceanic and Atmospheric Association, Washington, DC, U.S.A.
GPS	global positioning system	—
HF-DM	high-frequency delayed mode	—
IAG	International Association of Geodesy	Munich, Germany
IAPSO	International Association for the Physical Sciences of the Oceans	Goteborg, Sweden
ICSU	International Council for Science	global organization, based in Paris, France
IGS	International GNSS Service Central Bureau	based at the Jet Propulsion Laboratory, Pasadena, CA, U.S.A.
IOC	Intergovernmental Oceanographic Commission	UN, based in Paris, France
IPCC	Intergovernmental Panel on Climate Change	UN, based in Geneva, Switzerland
ITRF	International Terrestrial Reference Frame	
MSL	mean sea level	—
NOC	National Oceanography Centre	Liverpool, U.K.
ODINAFRICA	Ocean Data and Information Network for Africa	
PSMSL	Permanent Service for Mean Sea Level	Liverpool, U.K.
RLR	revised local reference	—
RSL	relative sea level	—
SONEL	Système d'Observation du Niveau des Eaux Littorales	La Rochelle, France
TIGA	GPS Tide Gauge Benchmark Monitoring Working Group	
UHSLC	University of Hawaii Sea Level Center	Honolulu, Hawaii, U.S.A.
UNESCO	United Nations Educational, Scientific, and Cultural Organization	UN, based in Paris, France
VLIZ	Flanders Marine Institute	Oostende, Belgium
WDS	World Data System	program of ICSU

of acronyms used in this article, see Table 1). Following the discontinuation of the Federation of Astronomical and Geophysical Data Analysis Services and the World Data Centres, the PSMSL is working toward membership in their successor, the new World Data System (WDS) of ICSU. The PSMSL also has a separate advisory group with members from the community invited to serve for a limited term by the director.

The database of monthly mean sea-level records has expanded enormously since it was founded in 1933 (for a history of the early years of the PSMSL, see Rossiter, 1963). For example, Woodworth (1991) reported that the data bank held 34,000 station-years of information, which had grown to nearly 49,000 by the time of Woodworth and Player (2003) at a rate of 1250 station-years *per* year. The data bank now exceeds 60,000 station-years, which is being added to at a rate of 1375 new station-years *per* year.

This paper is structured as follows: we first describe the make-up of the PSMSL data set, highlighting the main changes over the past few years and focussing on particular regional issues. We next describe the wider service aspects of the PSMSL and a selection of new products that have been launched or are currently under development. Next we report on recent agreed changes to the Global Sea Level Observing System (GLOSS) Core Network. Following this, we discuss developments in high-frequency data products and the ongoing integration of the PSMSL and the GLOSS Delayed-Mode Archive Centre data through our interaction with the British Oceanographic Data Centre (BODC). There then follows a discussion of issues surrounding uses of PSMSL data in geodesy and in the study of vertical land movement. We conclude with some thoughts on future developments and directions for the PSMSL.

THE PSMSL DATA SET

The PSMSL's main functions are acquiring and developing a global data set of monthly and annual mean sea-level information, checking its quality, and distributing it to the community. The primary source of the data is the global set of over 850 active tide gauges, which are operated by local and national authorities and supplied regularly to the PSMSL, usually on an annual basis. Quality control of the data is undertaken with a set of sophisticated tools that we have developed in Matlab® to allow "buddy checking" against nearby stations, visual comparison of rate changes between neighbouring stations and the data gaps within them, and interactive flagging of questionable data. Additionally, high-level quality control is done through the use of the data in scientific analyses by PSMSL staff (*e.g.*, Holgate and Woodworth, 2004; Jevrejeva *et al.*, 2006, 2008; Jevrejeva, Moore, and Grinsted, 2008; Woodworth, 1990, 2005; Woodworth *et al.*, 2009b, 2009c; Woodworth, Pouvreau, and Wöppelmann, 2010).

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 include descriptions of benchmarks and their locations, types of

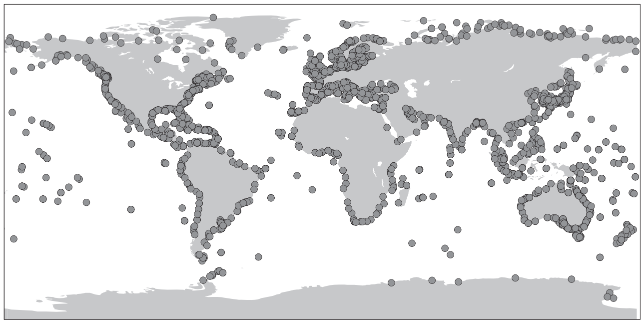

Figure 1. Distribution of all PSMSL stations, both research quality (RLR) and non–datum controlled stations (known as "metric only").

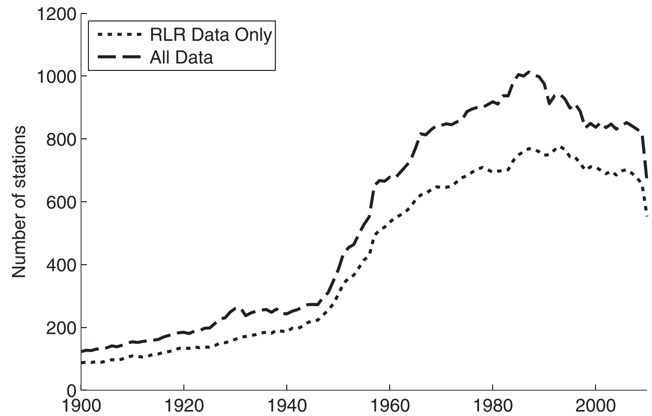

Figure 3. Data availability as a function of time. The decline in data since the mid-1980s is clearly apparent in both the full (metric) data set and the RLR data set.

instrumentation and frequency of data collection (where available), and 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). 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.

The PSMSL currently holds data from 2067 stations (not all of which are currently active) that are supplied by some 200 data authorities. The data records in the PSMSL are separated into two distinct sets. The first is a research quality set that is related to a consistent set of locally defined benchmarks through time. This data set is known as revised local reference (RLR). In contrast there are records that have no datum control and so are unsuitable for long-term rate estimates, though they may be useful for certain applications, such as in investigating short-term variations and in seasonal cycle studies. For historical reasons these data are known as the "metric only" data set.

Figure 1 shows the distribution of all these stations, both the RLR and the metric only. As has been noted by a number of authors (Church and White, 2006; Douglas, 1991, 1997; Holgate and Woodworth, 2004; Jevrejeva *et al.*, 2006; Woodworth, 1991; Woodworth and Player, 2003) the distribution of these stations in time is far from even. The mean record length of the RLR data is 37 years. For the complete metric data set (*i.e.*, RLR plus metric only), the mean record length is 29 years. However, for analysis of long-term trends, many authors (*e.g.*, Douglas, 2001) have pointed out that at least 60 years of data are required. This point is illustrated in Figure 2, which shows how longer records are primarily located in the Northern Hemisphere, with nearly all the very longest records (>100 years) located around Northern Europe and the Baltic Sea, except for a few stations in North America, Asia, and Australasia. Despite advances in the supply of data from many countries around the world, most of the PSMSL data set is still composed of contributions from a small number of major data suppliers. However, there are also a large number of other authorities each supplying data from a small number of stations. Since 2003, the PSMSL has added an average of 1600 station-years each year to the database. This number includes revised years of data that are provided periodically by suppliers.

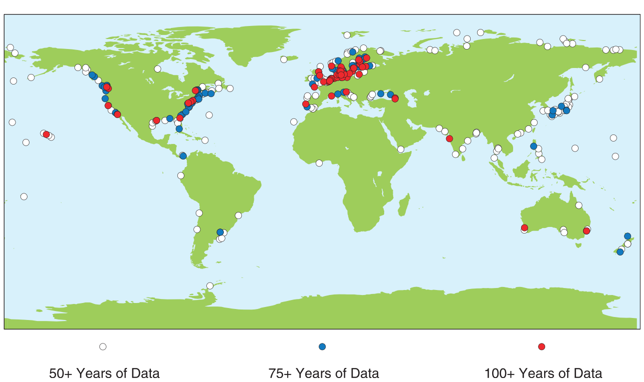

Figure 2. Distribution of long, research quality (RLR) records in the PSMSL data set.

It was noted in Woodworth and Player (2003) that there was an apparent fall off in the data receipts during the 1990s. At that time it was thought that this was primarily an artefact of the expansion in regional networks that had supplied data in the 1980s but that had struggled to be maintained during the 1990s. An earlier fall off during the 1980s had been reported by Woodworth (1991). In both cases, the drop in data receipts appeared to be resolved after some years' delay.

In contrast, the present analysis indicates that there is an ongoing issue leading to a long-term decline in data receipts (Figure 3), even though several regions have greatly improved their networks in recent years. Figure 4 illustrates the data receipts by continent and shows that all regions show a decline in the supply of tide gauge data. However, this average picture is somewhat deceptive, since each region also contains networks that are expanding. We discuss some of these issues in more detail below, but the major contributors to the decline appear to be from the European Arctic and South America. It is

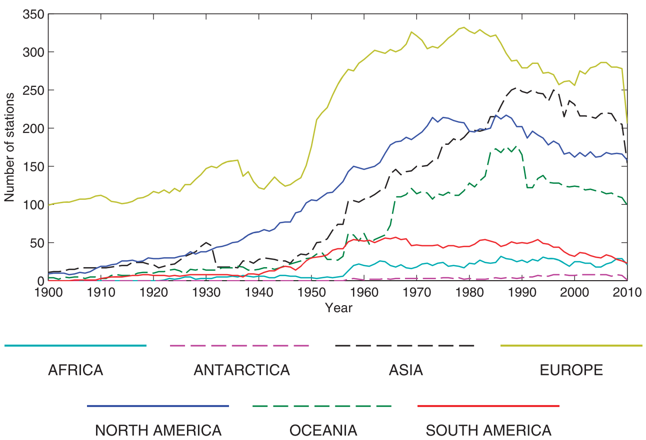

Figure 4. Data availability of the entire (metric) dataset for each year for each region.

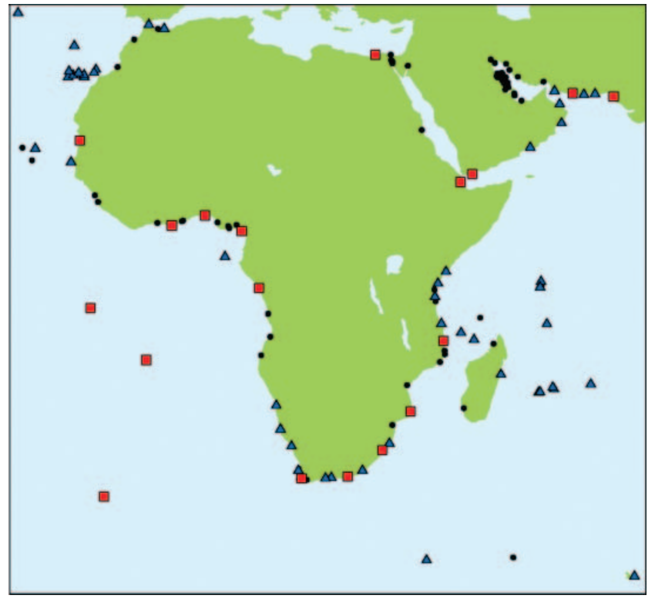

Figure 5. Tide gauge stations around the African continent. Red squares represent ODINAFRICA and other real-time upgraded sites that were supported by PSMSL engineers during their installation. Blue triangles show other currently active stations. Black dots represent historical sea-level records in the PSMSL database where we have not received data for more than 5 years.

important to note that delayed receipts to the PSMSL are much less of an issue now than previously due to faster data processing by many national authorities and faster and more reliable communication worldwide, with considerably more data being made available through web portals. Consequently, there does seem to have been a genuine decline in data receipts in recent years, undoubtedly for different reasons in different countries.

Overview of Major Areas of Change

There have been particular regions within the data set that stand out as having significant developments over the past several years, and some examples are given below.

Probably more time has been spent within the GLOSS programme in recent years on the topic of sea-level availability from Africa than from any other region. (An exception is perhaps the Indian Ocean region following the Sumatra tsunami.) The African continent contains a number of stations with long records. However, many of these have been discontinued, and for many years Africa has represented a major gap in the provision of global sea-level information. The main exceptions to this pattern are the tide gauges operated in South Africa since the mid-20th century (Woodworth, Aman, and Aarup, 2007).

In the last few years, attempts have been made to construct a new sea-level network for Africa, thanks to support from the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) within the GLOSS and Indian Ocean Tsunami Warning System programmes, and funding from the Government of Flanders, Belgium, within the Ocean Data and Information Network for Africa (ODINAFRICA) programme (Figure 5). Despite these major efforts at gauge installation, concern remains as to funding the long-term maintenance of the network and thereby the flow of sea-level information to data centres such as the PSMSL.

Several of the new stations have now served for several years in providing data for the construction of tide tables, for local operational oceanographic applications (*e.g.*, storm surge monitoring), and in tsunami warning. In addition, some stations have provided data that have enabled the recommencement of the discontinued long mean sea-level records (*e.g.*, Takoradi in Ghana, Woodworth *et al.*, 2009a).

The PSMSL has maintained a close linkage with engineers at the National Oceanography Centre (NOC) for the development of new technologies, installation of instrumentation, and the training of tide gauge operators. This end-to-end integration of measurement technology, data collection, quality control, and research has been fundamental to maintaining the highest standards in our work. The NOC in Liverpool has provided technical and logistical support as well as training for many of the new installations. At each site, NOC engineers have made recommendations for instrumentation and ancillary hardware and have tested equipment prior to installation. Subsequently, NOC engineers have provided support *via* telephone and email conversations to resolve postinstallation issues.

While the number of new installations has been impressive, a more important measure of success is in the amount and the quality of the data that these sites are contributing. Unfortunately, there have been many data outages for a number of reasons, and this situation will only get worse if the provision of spare parts is affected by lack of funding. The result is that many time series contain gaps of various lengths, which do not inhibit the use of the time series for some oceanographic studies, but does limit their usefulness to the PSMSL, which requires data sets to have fewer than 16 missing days of data to

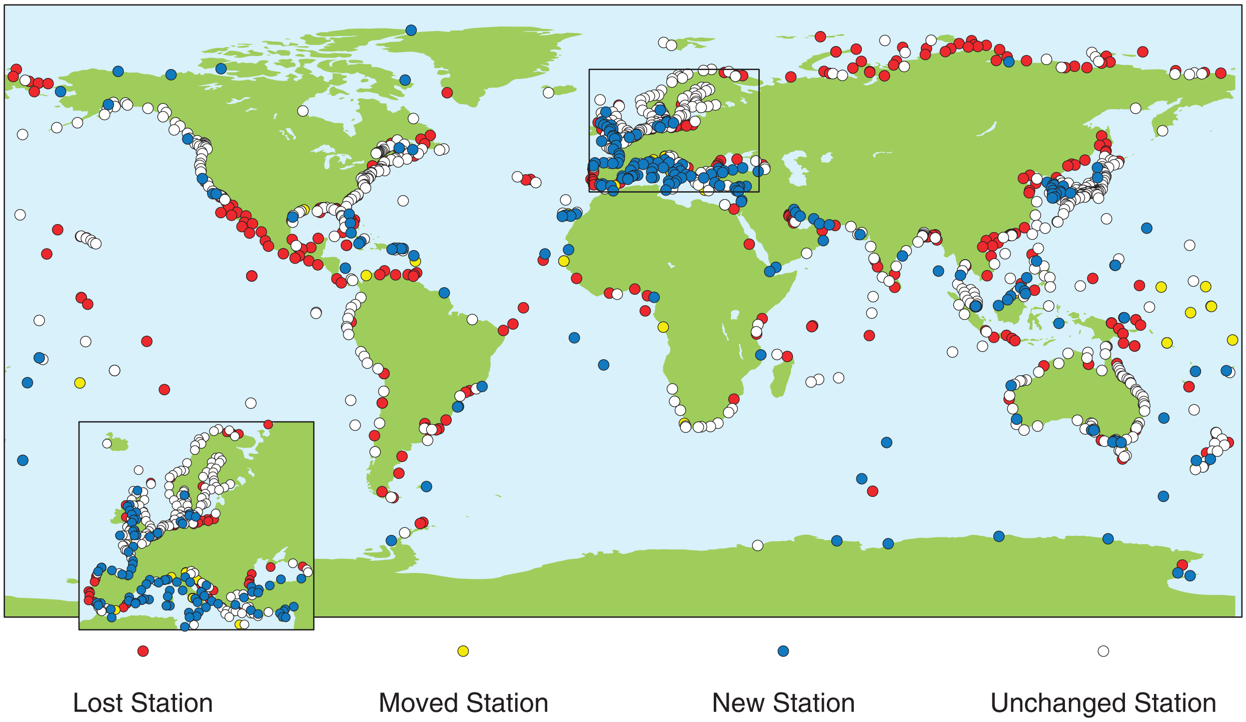

Figure 6. Comparison of data supply of the 5-year period 2006–09 with the peak period of data supply 1986–89. The inset shows an expanded view of the European region. The figure emphasises the areas that have contributed to the overall decline in the supply of stations to the PSMSL over this time span.

calculate a monthly mean and to have at least 11 months of data to calculate an annual mean.

A final comment concerning Africa is that there continues to be almost no data from the African Mediterranean coast, the long record from Ceuta in Spanish North Africa and the recent establishment of a new Alexandria tide gauge in Egypt being notable exceptions.

Polar regions represent difficulties for tide gauge operations owing to the environmental conditions as well as organisational and funding issues. The PSMSL and GLOSS attempted to highlight the need for sea-level measurements in polar regions during the International Polar Year of 2007–08 (Turner *et al.*, 2009) but without a great deal of success. In brief, while Antarctica is now served by a sparse but probably adequate tide gauge network (*e.g.*, Hibbert *et al.*, 2010), the Arctic continues to require more investment in long-term sites on the Canadian, Greenland, and Russian coasts.

In 2003, the Arctic and Antarctic Research Institute in St. Petersburg contributed a large quantity of data from the Russian Arctic to the PSMSL. This has led to a considerable improvement in the coverage of this region in the database.

The changes between the peak period of data supply to the PSMSL (1986–89) and the recent period (2006–09) are shown in Figure 6. Unfortunately, as can be seen, many of the Russian Arctic stations have been discontinued during the last decade, and this factor has been a major reason for the decline in the European contribution to the catalogue in recent years (Figure 4). There was also a marked reduction in the number of Canadian Arctic tide gauge stations during the 1980s and 1990s, although four have been reestablished recently (Figure 6). In Greenland, data from three new stations are being provided in real time by the Technical University of Denmark, and it is anticipated that these records will be included in the PSMSL in due course.

Although Europe is generally well covered by tide gauges, there are still some difficulties in data supply, especially with regard to real-time information from the eastern Mediterranean, where sea level is also required for tsunami warnings (Woodworth, Rickards, and Pérez, 2009). Data delivered to the PSMSL from new stations in the Mediterranean have not been enough to make up for overall losses in Europe.

On a more positive note, many countries have overseen major expansions in their sea-level monitoring or in newly reinstrumenting their stations. The status of monitoring in many individual countries can be obtained from the national reports to the regular GLOSS Group of Experts meetings (www.gloss-sealevel.org). From inspection of Figure 6, it is clear that the major gaps in PSMSL coverage remain in South America, Africa, and Asia, and the PSMSL will be working closely with the IOC GLOSS programme to ensure that data become available from these areas in future.

The Need for Continuity of Long Time Series

For the investigation of long-term trends in sea level such as those used in analyses for the Intergovernmental Panel on

Climate Change (IPCC) assessment reports (Bindoff *et al.*, 2007; Church *et al.*, 2001), it is particularly important to maintain high-quality records spanning many decades. Unfortunately, a number of such records have been terminated in recent years. For example, of the 21 stations with long records employed by Douglas (Douglas, 1991, 1997, 2008), we have been unable to acquire updates for Cristobal in Panama, Quequen and Buenos Aires in Argentina, Cascais and Lagos in Portugal, and Auckland in New Zealand. Of these, data exist for three stations, but reductions in funding and other issues have led to the cessation of supply. With help from the PSMSL in processing and quality control of the data, Cascais and Lagos should eventually be brought up to date. In the case of Buenos Aires, the development of the port led to a relocation of the gauge, breaking the continuity of the series. A similar situation arose with Cristobal in Panama, which has been replaced by the Coco Solo tide gauge, but unfortunately there is no levelling connection between the benchmarks at the two sites. Such problems highlight the importance of continued funding and support for long-term observing systems such as those in the Global Climate Observing System (GCOS, 2010).

Data Archaeology

Many historical tide gauge data still exist in nondigital 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; http://uhslc.soest.hawaii.edu/), 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 nondigital 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. In the future, coordination of a tide gauge data rescue project with the Atmospheric Circulation Reconstructions over the Earth programme (carrying out rescue of air pressure data) could result in interesting synergies.

Scientific Uses of the PSMSL Data Set

As stated in the introduction, data from the PSMSL have a wide variety of uses in a number of different scientific disciplines, including geodesy, oceanography, geology, and climate change studies. Over the past decade, we know of an average of at least 39 peer-reviewed papers *per* year published in leading journals that cite the PSMSL data set. This has led to a total of over 5500 citations of papers using PSMSL data over the past 10 years.

Chapter 5 of the IPCC 4th Assessment Report (Bindoff *et al.*, 2007) contained citations of 28 papers that used the PSMSL data for long-term global trend reconstruction. In addition, tides, ocean transport, extreme levels, storm surges, and tsunamis have all been studied with the GLOSS delayed-mode high-frequency data detailed below (*e.g.*, Bernier and Thompson, 2006; Egbert and Ray, 2003; Holgate *et al.*, 2008a, 2008b; Matthews and Meredith, 2004; Platzman, 1991; Pugh and Vassie, 1979; Rabinovich and Thomson, 2007; Rabinovich, Thomson, and Stephenson, 2006; Ray, 2001; Sanchez, 2008; Tawn, 1992; Tsimplis, 1997).

As will be discussed in more detail below, a major innovation over the past decade or so is the use of Global Navigation Satellite Systems (GNSS) to complement tide gauge measurements and allow the calculation of geocentric sea-level change. The PSMSL works closely with the Système d'Observation du Niveau des Eaux Littorales (SONEL) in La Rochelle, France, to associate tide gauges with nearby GNSS stations and related benchmarks. Each tide gauge that is within 20 km of a GNSS station is hyperlinked from the relevant PSMSL page to the SONEL station information. As a result, geodetic data on rates of vertical land movement are easily available. Several papers making use of the linked GNSS/tide gauge records have been published in recent years (*e.g.*, Bouin and Wöppelmann, 2010).

A WIDER SERVICE: PRODUCTS AND TRAINING

The usability of the PSMSL website improved in April 2010 with the launch of a redesigned site and a new web address: www.psmsl.org. Central to this development is a new database with a structure optimised for web use. We now provide regular weekly date-stamped updates in contrast to the approximately semiannual revisions that were previously provided.

To aid reproducibility of results in papers, an annual release of the data has been made available. The PSMSL appreciates the acknowledgement of authors in their papers and recommends that users of PSMSL data include the date on which they downloaded information from the dataset when citing its use.

Each tide gauge now has a permanent unique identifier and its own dedicated page with an interactive Google® map that introduces the ability to navigate to nearby stations. The list of stations can also be sorted in a number of different ways to make finding the relevant data easier.

Alongside the website and database is a new delivery system that is continuing to evolve. Documentation and benchmark diagrams are now automatically downloaded with the corresponding data. Recent updates are highlighted, and the date of last update for each station is now provided. We also have moved to the inclusion of ISO 3166 country codes to help maintain continuity during changes in political boundaries and internationally agreed naming conventions.

A number of new products have been developed in addition to the main data set. These include easy-to-use interactive viewers for anomaly and trend maps, examples of which are shown in Figures 7a and b. The PSMSL also provides a Google Earth® kml file for exploring the global data set. This file allows a user to easily navigate to a station and display the annual and monthly mean time series. It also provides links to the data, datum information, and the station page on the PSMSL website.

The PSMSL also maintains its strong commitment to training. In addition to the many resources available through

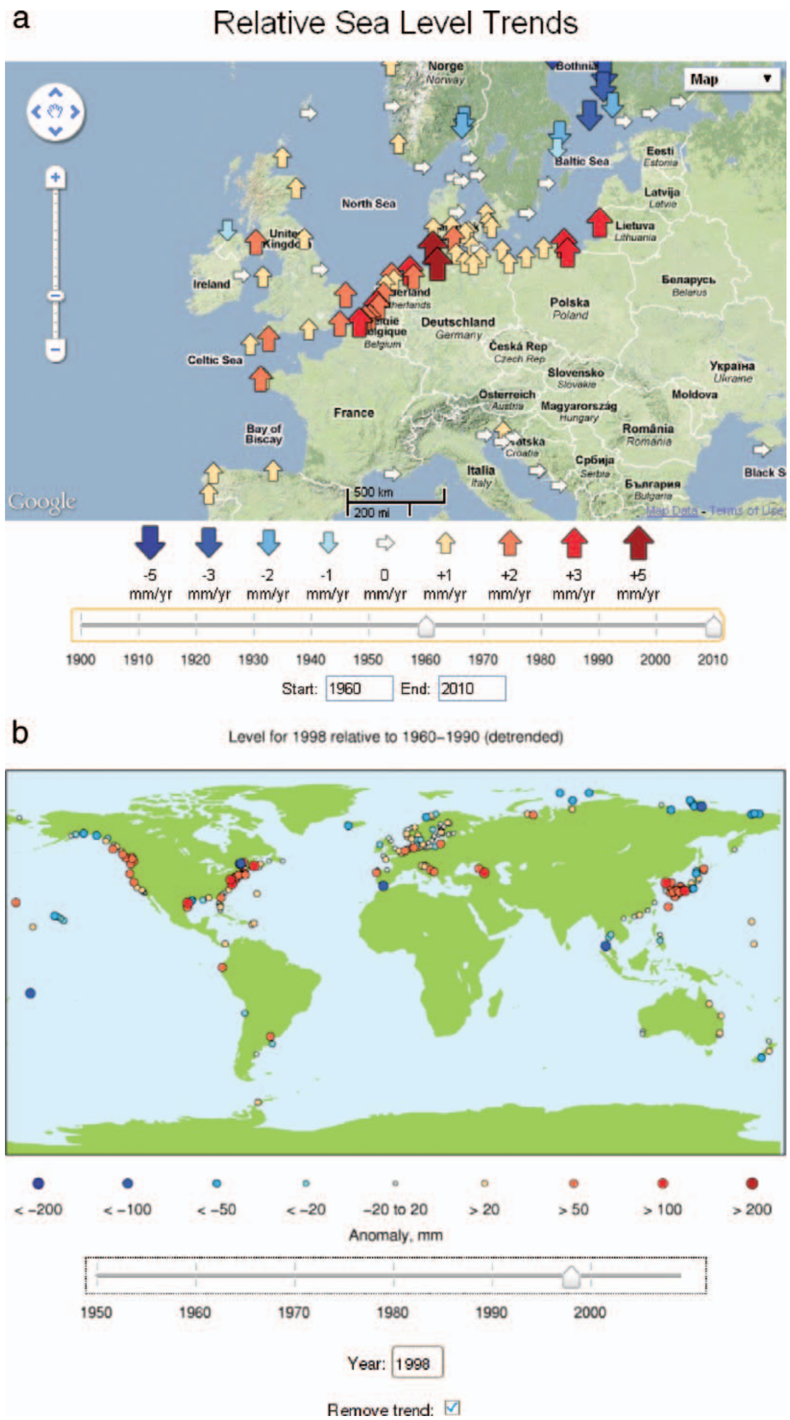

Figure 7. Examples of (a) the new interactive trend viewer and (b) the interactive sea-level anomaly viewer on the PSMSL website.

the PSMSL website, we have continued our involvement with IOC/GLOSS sponsored training over the past decade. These include courses in the Servicio Hidrografico y Oceanografico de la Armada de Chile (2003); Kuala Lumpur, Malaysia (2004); and Oostende, Belgium (2006). In addition, we have hosted IOC Fellows from several countries, including Egypt, Iran, Nigeria, Kenya, Indonesia, Pakistan, Sri Lanka, the Republic of Congo, and Ivory Coast. All of this training is carried out with the aim of building local capacity for sea-level work, which will ensure future data receipts and has significant economic as well as scientific benefits.

Engineers and scientists from PSMSL have also provided support for tide gauge installations in a number of locations in Africa, the Middle East, Pakistan, and Sri Lanka. Much of this support has been in relation to real-time monitoring systems. These systems were developed at NOC in Liverpool in response to the Indonesian tsunami in 2004 and make use of Inmarsat's Broadband Global Area Network (BGAN) as well as the Meteosat data collection platform system (Holgate *et al*., 2008a, 2008b; Holgate, Foden, and Pugh, 2007). In engaging in these roles, PSMSL has continued in its core mission to contribute to the wider sea-level community.

DEVELOPMENTS IN THE GLOBAL SEA-LEVEL OBSERVING SYSTEM

The IOC GLOSS programme has been a major contributor to the improvements in the global tide gauge network since the mid-1980s (Merrifield *et al*. 2009). Since the last review of the work of the PSMSL, GLOSS has also developed a new website with a separate domain from the PSMSL (http://www.gloss-sealevel.org). The IOC GLOSS programme has been extremely successful in setting technical standards and providing training for tide gauge operators. With the continued support of the IOC, the PSMSL has provided a major input to the management of GLOSS alongside the UHSLC. One of the first components of the Global Ocean Observing System, GLOSS has expanded its role beyond the original aim of improving the supply of monthly mean sea levels to the PSMSL. The GLOSS workshops have also included aspects of sea-level science, such as technical guidance in the use of GNSS to link local tide gauge benchmarks into a consistent reference frame and specifications for tsunami monitoring.

One of the key goals of GLOSS is to define a core network of tide gauges that are spread as evenly as possible around the world to reduce bias in global sea-level measurements. This core network has undergone several revisions over the years in a pragmatic effort to close the gap between the aspirational network as originally envisioned and the reality of installed gauges. A new GLOSS implementation plan has recently been published, and the latest incarnation of the network, GLOSS10, is now 82% complete with 238 of the 290 gauges installed and sending data, based on receipts since 1995.

"Fast" and "real-time" data have become increasingly important in recent years. "Real-time data" are raw data in their native frequency, which are delivered with no quality control whatsoever. "Fast data" are high-frequency (hourly or above) data that are made available within 1–2 months of collection with a basic quality control applied. In contrast, the more rigorous standards of the "delayed-mode data" quality control means that it often takes a year or longer before it becomes available. Fast data are often used in, for example, the validation of operational ocean forecasting models and as a check on altimetric sea-level fields (*e.g*., Mitchum, 2000). Globally distributed real-time data, often from remote locations, was unimaginable even a few years ago. However, since the Indonesian tsunami of 2004, the imperative for real-time data has become much greater. Tide gauges are not a primary component of an early warning system but are extremely useful for validating tsunami models, and these can provide warnings to more distant locations. For this reason the GLOSS standard for tide gauge stations strongly recommends that they are designed for multiple purposes so that the data can serve a number of uses over timescales ranging from that of tsunamis (a few minutes) to changing climate (decades to centuries).

With vastly improved communication systems around the globe, there has developed an increased requirement for fast and real-time data. The GLOSS fast data centre is based at UHSLC, and there is also a real-time sea-level monitoring centre at the Flanders Marine Institute (VLIZ; available at www.ioc-sealevelmonitoring.org). The PSMSL works closely with both these organisations and continues to improve links between the respective websites.

A significant hurdle to deploying communications across the global network has been the lack of sufficient bandwidth on existing satellite systems such as Meteosat and the Geostationary Operations Environmental Satellites (GOES). Thus the number of tide gauges communicating through these systems was very limited, and the frequency of data transmission constrained to every 15 minutes in most cases. A few U.S. stations communicate more frequently (every 6 minutes) through GOES, and planned upgrades to Meteosat (high rate data collection platform) will eventually allow European operators to transmit at rates of up to once *per* minute (Burns, 2012; EUMETSAT, 2011). However, the advent of mobile broadband systems based on general packet radio service and BGAN has made real-time, bidirectional communication possible already. Bidirectional communication has the additional benefit of allowing remote diagnostics and reconfiguration "over the air" (Holgate *et al*., 2008a, 2008b; Holgate, Foden, and Pugh, 2007).

HIGH-FREQUENCY SEA-LEVEL DATA: THE GLOSS DELAYED-MODE DATA ARCHIVE

Over the past few years, the PSMSL has linked more closely to delayed-mode high-frequency data held by BODC. Originally a product of the World Ocean Circulation Experiment and the follow-on project of the Climate Variability and Predictability Programme in 2002, the delayed-mode high-frequency data from the GLOSS core network have continued to be quality controlled and archived by BODC, now designated the GLOSS data archive. This joint venture aims to eventually provide seamless access to the high-frequency data from GLOSS stations from the PSMSL station pages. The high-frequency delayed-mode (HF-DM) data set is research quality data that is useful for examining tides (Woodworth *et al*., 2005b), extreme sea levels (*e.g*., Menéndez and Woodworth, 2010; Woodworth, Menéndez, and Gehrels, 2011), tsunamis (Woodworth *et al*., 2005a), and processes such as wave propagation (Hughes *et al*., 2003), as well as many other geophysical phenomena (*e.g*., Ponte and Lyard, 2002; Woodworth *et al*., 2002).

The HF-DM data are archived at their supplied frequency (hourly or greater) and are made available after a high level of quality control that requires at least a year of data and so is typically updated every 12 months. Any additional parameters (*e.g.*, meteorological data) recorded are also stored alongside the sea-level data. This is in contrast to the UHSLC "fast mode" GLOSS data set that is uniformly reduced to hourly frequency and is typically supplied after one month. A further difference between the two data sets is the quality control procedures. The PSMSL/BODC add flags to data which are considered suspect, whereas the UHSLC removes such data from the time series and may also interpolate short gaps. The rationale behind the PSMSL/BODC approach is that there may be information in the subhourly frequencies. Poor quality data that appears unsuitable for applications such as trend analysis may nonetheless be useful under particular circumstances.

In the immediate future, links between the HF-DM data and PSMSL will be *via* a link from the PSMSL station page to the GLOSS Station Handbook (GSH; http://www.gloss-sealevel.org/station_handbook/) page. The GSH pages are being refreshed to add location maps and will combine metadata from the PSMSL so that there is a single source of location data. This is to avoid previous issues with slightly different details being maintained between the two organisations. An issue that arises when combining such station information is that, for historical reasons, different organisations sometimes refer to the same station by a different name. For this reason, the PSMSL will list alternative names to help reduce confusion.

SEA LEVEL AND VERTICAL LAND MOVEMENTS

Sea level measured by a tide gauge is a height relative to the level of benchmarks on the nearby land (called relative sea level [RSL]), so vertical motion of land will cause an apparent sea-level change. This is the most relevant sea-level measurement for society, in that this local measure of sea-level change is what determines inundation of coastal communities. However, in some scientific studies it is desirable to remove the effects of the local land movement from a tide gauge record, *e.g.*, when comparing with satellite radar altimetry measurements of sea surface height (Mitchum, 2000). In addition, some processes, whose contributions to RSL are dominated by vertical land movement, could bias the global average sea-level rise caused by present-day changes determined from tide gauges. The two most common means of addressing this problem are the use of predictions of rates of vertical land movements from Earth models and the use of GNSS (or, formerly, global positioning system [GPS]) measurements.

It is clear in many mean sea-level (MSL) records that vertical land movements can be as large, or larger, than those of the ocean itself. These movements can be both slow and monotonic, such as those due to the continued response of the Earth and oceans to the end of the last ice age (glacial isostatic adjustment [GIA]), or irregular, such as those due to tectonic events. The book by Emery and Aubrey (1991) contains many examples of geological signals in sea-level records.

Because GIA is the best modelled geological process for which global predictions are available, many analysts of MSL data adjust the records for the GIA contribution using a geodynamic model of the solid Earth (*e.g.*, Peltier, 2004). Without such a correction, global estimates from the longest tide gauge records could be biased, since these occur primarily in regions relatively near the former centres of the large ice sheets. These predictions account for both the vertical land movement and the associated changes to the geoid, which can be of the order of several tenths of a millimetre per year to millimetres per year in magnitude (*e.g.*, Shennan, Milne, and Bradley, 2011).

Increasingly, the community is equipping tide gauges with GNSS and other geodetic systems such that vertical land movements, of whatever origin (*i.e.*, local subsidence through to GIA), can be measured within a global reference frame. The IOC manuals on sea-level measurement and interpretation (the latest being Aarup *et al.,* 2006) provide advice on the operation of GNSS equipment at tide gauge sites, together with requirements for local benchmark networks. The GPS Tide Gauge Benchmark Monitoring Working Group (TIGA) of the International GNSS Service provides a coordination mechanism for gathering experience of using GNSS in this way (Blewitt *et al*., 2010).

Since some local changes recorded by tide gauges, such as subsidence and ground water extraction, are dominantly due to vertical land moment, some analysts simply "correct" tide gauge records for vertical movement using GNSS, and encouraging recent developments have taken place in such studies (*e.g.*, King *et al*., 2012; Wöppelmann *et al*., 2009). However, since subsidence and groundwater extraction also change the geoid, this portion of the signal is not corrected by the GNSS.

In addition, GNSS is also required at a tide gauge to position the sea-level measurements obtained by the gauge within a geocentric reference frame for comparison to satellite altimeter data (*e.g.*, Mitchum, 2000). The GNSS, altimeter, and other geodetic measurements take place within a global frame of which the International Terrestrial Reference Frame (ITRF) is a realisation (Blewitt *et al*., 2010). This frame is in turn defined in terms of a number of geodetic techniques including GNSS, Doppler orbitography, and radiolocation integrated by satellite, satellite laser ranging, and very long baseline interferometry. New releases of the ITRF are issued from time to time (Altamimi, Collilieux, and Métivier, 2011), with the latest available being ITRF 2008.

The PSMSL, together with the TIGA and other projects, is planning to provide more detailed linkage between sea-level information and the GNSS data sets now available from processing centres.

The Global Geodetic Observing System

The measurement of sea level has always had an important role in geodesy because of its close correspondence to a level surface (the geoid). Sea level measured at a tide gauge over an extended period has been used in many countries as a reference level for their national datums, *e.g.*, Ordnance Datum Newlyn in the U.K. (Pugh, 1987). In other countries, sea levels measured at a number of gauges have been used as constraints on least-squares adjustments of national levelling campaigns *e.g.*, in the historical Canadian datum CGVD28 (Véronneau, Duval, and Huang, 2006).

The Global Geodetic Observing System (GGOS, http://www.ggos.org/) is a programme of the IAG with the aim of coordinating and integrating the observing systems of geodesy into a form that can serve the needs of science and society (Plag and Pearlman, 2009). A main responsibility of GGOS is to ensure the provision of the global geodetic infrastructure needed to maintain and enhance the ITRF (Blewitt *et al*., 2010). Consequently, fundamental contributions to the work of the GGOS Steering Committee come from the International GNSS Service (formerly the International GPS Service) and other IAG "positional services." A second set of major contributions come from IAG Services concerned with the gravity field and geoid; these are now grouped into an International Gravity Field Service. Finally, because of the importance of sea level to geodesy as indicated above, the PSMSL has also been a regular contributor to the committee.

FUTURE DEVELOPMENTS

The PSMSL remains an essential service with an evolving role in a number of scientific and technical areas while maintaining its particular focus on long-term sea-level change and variability. Our work will continue to contribute to the understanding of many aspects of sea-level changes including our involvement with important international activities such as the regular IPCC Scientific Assessment Reports.

Exciting future developments include the integration of the high-frequency delayed-mode data from BODC with the PSMSL's annual and monthly means. We are also working to link the PSMSL station web pages with those of UHSLC for fast mode tide gauge data and with VLIZ for real-time sea levels, and we expect these links to be live by the end of 2012. The recently formed ICSU World Data System will strive to be a "community of excellence" for scientific data, ensuring the long-term stewardship and dissemination of quality assessed data and data services to the international scientific community. It aims to transition from the previous stand-alone data centres and services to a common globally interoperable, distributed data system that incorporates emerging technologies and new scientific data activities. The PSMSL has been working toward membership of the WDS, and this should be confirmed soon.

One of the most exciting new initiatives that will be coming online is the European Sea Level Delayed-Mode Data Portal. Hosted by BODC, this sea-level portal will be a central point of access for quality controlled sea-level data from across Europe, not just GLOSS stations. The portal aims to allow the searching and downloading of data from the entire European sea-level dataset and will therefore greatly improve and simplify access. Ownership of the data remains clearly with the national authorities, who are also responsible for quality control of the data. Currently in active development, it is hoped that this service will also be available to accept data contributions from the end of 2012.

We are continually developing the PSMSL website and are aiming to launch some improved data exploration capabilities in the near future. Our commitment to training tide gauge operators and supporting local capacity building in developing countries will remain undiminished.

Overall, the PSMSL has experienced significant growth and an eventful decade and we are looking forward to celebrating our 80th birthday in 2013.

ACKNOWLEDGMENTS

We would like to thank all the tide gauge authorities from around the world who have provided sea-level data to the PSMSL for so many years. We also wish to thank the international community of sea-level scientists who continue to demonstrate the importance of the data bank through their use of the data in their work. In addition, we would like to thank present and past colleagues at NOC in Liverpool and colleagues at the IOC (especially Thorkild Aarup) for their help with PSMSL activities.

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