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DATA PAPER

Towards a global higher-frequency sea level dataset

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This paper describes the assembly of an updated quasi-global dataset of higher-frequency sea level information obtained from tide gauges operated by many agencies around the world. We believe that the construction of such a dataset is fundamental to scientific research in sea level variability and also to practical aspects of coastal engineering. A first version of the dataset was used in approximately a dozen published studies, and this second version is about twice the size, containing longer and more geographically representative sea level records. The dataset has acquired a digital object identifier and may be obtained from several sources. The paper mentions some of the merits of and deficiencies with the present version and takes a forward look at how the dataset may be updated in the future.

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Dataset

This dataset is called Global Extreme Sea Level Analysis Version 2 (GESLA-2) which contains higher-frequency sea level information from stations distributed worldwide (39 151 station-years of data from 1355 station records). The dataset is available from http://www.gesla.org and is also distributed by the British Oceanographic Data Centre with doi identifier as follows:
Identifier: doi:10.5285/3b602f74-8374-1e90-e053-6c86abc08d39
Creators: Woodworth, P. L., J. R. Hunter, M. Marcos Moreno, P. C. Caldwell, M. Menendez and I. D. Haigh
Title: GESLA (Global Extreme Sea Level Analysis) high frequency sea level dataset
Publisher: British Oceanographic Data Centre – Natural Environment Research Council, UK
Publication year: 2016
Resource type: Dataset
Version: 2

Introduction

This paper is concerned with obtaining a global dataset of higher-frequency sea level records from tide gauges at as many locations worldwide as possible. Such records are required for a wide range of oceanographic research and for practical applications in coastal engineering.

There are two components of such an aim. One component is concerned with encouraging countries to install tide gauges at locations where none exist at present, to operate them to internationally agreed standards, and to make the data available to interested users. This aspect is a primary objective of the Global Sea Level Observing System (GLOSS) of the Intergovernmental Oceanographic Commission (IOC) (IOC, 2012).

A second component is concerned with the collection of data from the global set of tide gauges, whether individual gauges have originated through the GLOSS programme or not, and to make the data available to users for a wide range of applications. Because most tide gauges are owned and operated by national agencies, this objective requires the combination of sea level information held in many national, and some international, databanks, in which the data are stored in many different ways. This presents anyone interested in making quasi-global sea level studies with the major task of combining information from many sources into a unified dataset with each record capable of analysis by the same methods.

We describe below how we have assembled such a unified dataset that we call GESLA (Global Extreme Sea Level Analysis) which is finding application by a number of researchers. As well as providing information on this dataset, the present paper is intended to give some background on what other datasets are available, and to make the case for the regular updating and extension of the GESLA dataset in the future.

The 'sea level data' in question is what is usually called 'higher-frequency', 'delayed-mode' information. 'Higher frequency' indicates the sampling of sea level every hour or more frequently (e.g. 6 or 15-min) as originally required by the GLOSS programme (IOC, 1990, 1997). This enables the study of extreme sea levels, ocean tides, storm surges, and some other coastal processes on a quasi-global basis. The 'higher' (in the jargon of the subject) indicates faster sampling than the 'mean values' of sea level such as the monthly and annual mean sea level (MSL) values collected and distributed by the Permanent Service for Mean Sea Level (PSMSL, Holgate *et al.*, 2013). 'Delayed mode' means that the data become available to users with a delay that can be from days to years following the recording by the tide gauge. This delay enables data centres to perform a thorough inspection and quality control, including the assignment of flags to show subsequent users whether data are good, suspect or bad. Delayed-mode processing is essential to ensure the quality of data used in scientific research.

There are other types of sea level data, and the following brief discussion distinguishes the types which are our primary interest from those that are not. The data types divide by both sampling and latency. Of course, all data types have important applications and the same tide gauges can meet all requirements (for a more detailed discussion, see Pugh and Woodworth, 2014; Woodworth *et al.*, 2015; Table 8.1 of IOC, 2016 provides a list of websites where each type of data may be obtained).

As regards sampling, even higher-frequency data, with 1-min or faster sampling, are required for the detection of tsunamis and other rapid processes such as meteotsunamis and seiches; GLOSS has extended its remit in recent years to meet the needs of tsunami warning systems (IOC, 2012, 2016). At lower frequency, the PSMSL has in fact always had a good global coverage, primarily because agencies have historically been more willing to share MSL values than higher-frequency data (Holgate *et al.*, 2013). These two extremes of the sampling spectrum are not addressed in this paper.

As regards latency, sea level data can be classified as 'real (or near-real)-time' (RT), 'fast', and 'delayed-mode' (D-M) information. Real-time data are required for operational purposes such as port operations, storm surge flood warning or tsunami identification; there is no requirement for, or possibility of, rigorous quality control. Data are often monitored around the clock by experienced personnel who will be able to judge whether any data anomalies are real or due to instrument malfunction. Fast data are required on timescales of days to weeks and so may have been subjected to some quality control. They are required for applications such as satellite altimeter data validation. The most common form of D-M data has historically comprised spot values of sea level every hour, obtained from inspection of the ink trace on a tide gauge chart. An analyst would smooth through any high-frequency variability in the trace due to seiching before estimating the hourly values. Nowadays, the data loggers of tide gauges provide their data electronically. Data can be either spot values, integrated (averaged) values over specified periods (e.g. 6 min) or integrated over a specified period within a longer sampling period (e.g. averaged over 3 min every 6 min). These D-M data, and not real-time or fast data, are our concern in this paper.

The following Section 1 describes the existing international sea level databanks and explains how they came into existence as sources of higher-frequency D-M data. Section 2 explains the origins of the GESLA dataset and provides information on its spatial and temporal coverage. Section 3 discusses how the sea level community might consider taking things forward in the future.

1. Present delayed-mode databanks

There are many agencies around the world from which one can obtain D-M sea level data. These include national authorities concerned with flood warning, naval hydrographic organizations, port authorities responsible for safe navigation, geodetic agencies, scientific organizations such as university research groups, and even a small number of individuals who operate tide gauges for their own interests. A list of such agencies can be obtained from the PSMSL website (http://www.psmsl.org/links/sea_level_contacts/).

However, the main databanks of accessible sea level data, organized on either a regional or global basis, have been those which originated through the major international oceanographic research programmes of the 1980s and 1990s, and which evolved into the sea level databanks of the GLOSS programme. This includes in particular the University of Hawaii Sea Level Center (UHSLC) which has a history stemming from the Pacific and Indian Ocean research of Professor Klaus Wyrtki. The Hawaii sea level activities became an essential component of the Tropical Ocean Global Atmosphere (TOGA) programme of the World Climate Research Programme (Kilonsky and Caldwell, 1991; McPhaden *et al.*, 1998), and a TOGA Sea Level Center (TSLC) was introduced in 1985. In 1990, the TSLC extended its geographical remit from the tropical Pacific and Indian oceans to include the tropical Atlantic.

A later, and larger, international activity during the 1990s was the World Ocean Circulation Experiment (WOCE), which was largely designed around the availability of sea level measurements from both tide gauges and satellite altimeters (Woodworth *et al.*, 2002). WOCE took advantage of the progress in sea level measurements in the Pacific and other tropical areas through TOGA. In addition, WOCE had a special focus on the circulation of the Southern Ocean, which benefited from the development of new sea level networks in the South Atlantic (Spencer *et al.*, 1993; Woodworth and Hibbert, 2015), southern Indian Ocean (Testut *et al.*, 2012), and Antarctica (ACCE, 2016). The responsibility for collecting and distributing sea level information for WOCE was delegated to the UHSLC (as the TSLC had by then been renamed) and the British Oceanographic Data Centre (BODC).

The WOCE sea level activities took place alongside those of the GLOSS programme of IOC. GLOSS was proposed in the mid-1980s by Dr. David Pugh (of what was then called the Proudman Oceanographic Laboratory, now the National Oceanography Centre Liverpool) and Prof. Wyrtki as a means of ensuring the long-term provision of worldwide sea level information from tide gauges to the PSMSL and to international oceanographic programmes such as WOCE (IOC, 1990).

The ongoing status of the main component of GLOSS, called the GLOSS Core Network (GCN), can be found at http://www.gloss-sealevel.org and http://www.psmsl.org/products/gloss. RT sea level data from GLOSS sites are sent to national data centres, regional tsunami warning centres, and the IOC Sea Level Station Monitoring Facility at the Flanders Marine Institute (VLIZ, Belgium) (http://www.ioc-sealevelmonitoring.org). Both RT and fast information are collected at UHSLC. Meanwhile, D-M information from GLOSS sites is the responsibility of the GLOSS Delayed Mode Centre at BODC (http://www.bodc.ac.uk). However, the holdings of the GLOSS D-M Centre are far from complete, and data from this source are used by only a small number of researchers. IOC (2016) gives further details of the centres from which each type of sea level data can be obtained.

As mentioned, UHSLC is charged with providing GLOSS with its RT and fast functions. However, in fact it has for many years also had a D-M function of its own called the research quality dataset (RQDS). The RQDS is archived as the Joint Archive for Sea Level (JASL) which is a collaboration between the UHSLC and the US National Centers for Environmental Information (Caldwell and Merrifield, 2015). The JASL acquires hourly datasets from GLOSS and non-GLOSS tide gauges that have received a final quality assessment from the data originators. JASL provides an independent check of the data, primarily to identify any remaining outliers, timing issues or datum shifts. Any quality issues with the data are brought to the attention of the data originators for reconciliation. JASL then assembles a single hourly time series for each station, or a series of subrecords if datum changes occur over time. The JASL dataset therefore represents a 'data product', as problematic data points are not simply flagged and left in the records (as they are by BODC for the GLOSS D-M dataset) but are actually changed to best assessed values by JASL. Any changes are documented in the metadata information.

The uniform hourly sampling of the records in JASL distinguishes the product from that of the BODC GLOSS-DM activity, in that the latter provides either hourly or subhourly values, depending on the frequency of the original recording (e.g. 6 min), together with ancillary variables (e.g. atmospheric pressure)

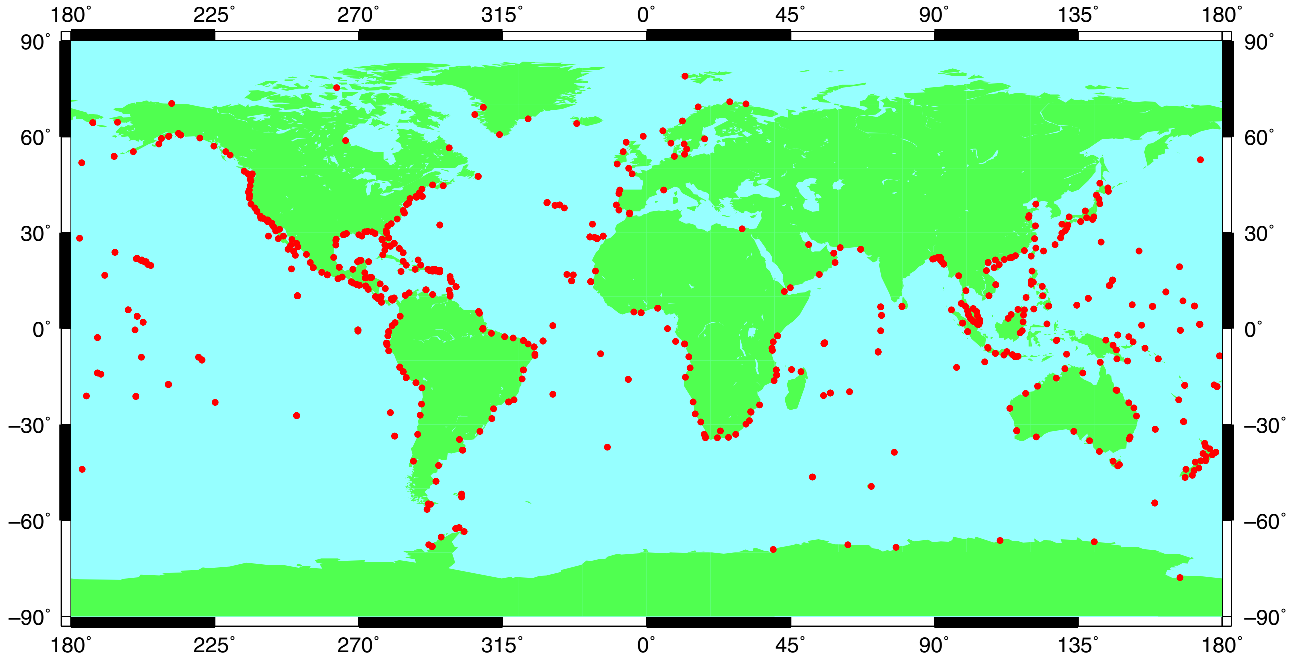

Figure 1. Locations of stations in the Joint Archive for Sea Level of UHSLC/NOAA (689 records with 17 369 station-years as of November 2016).

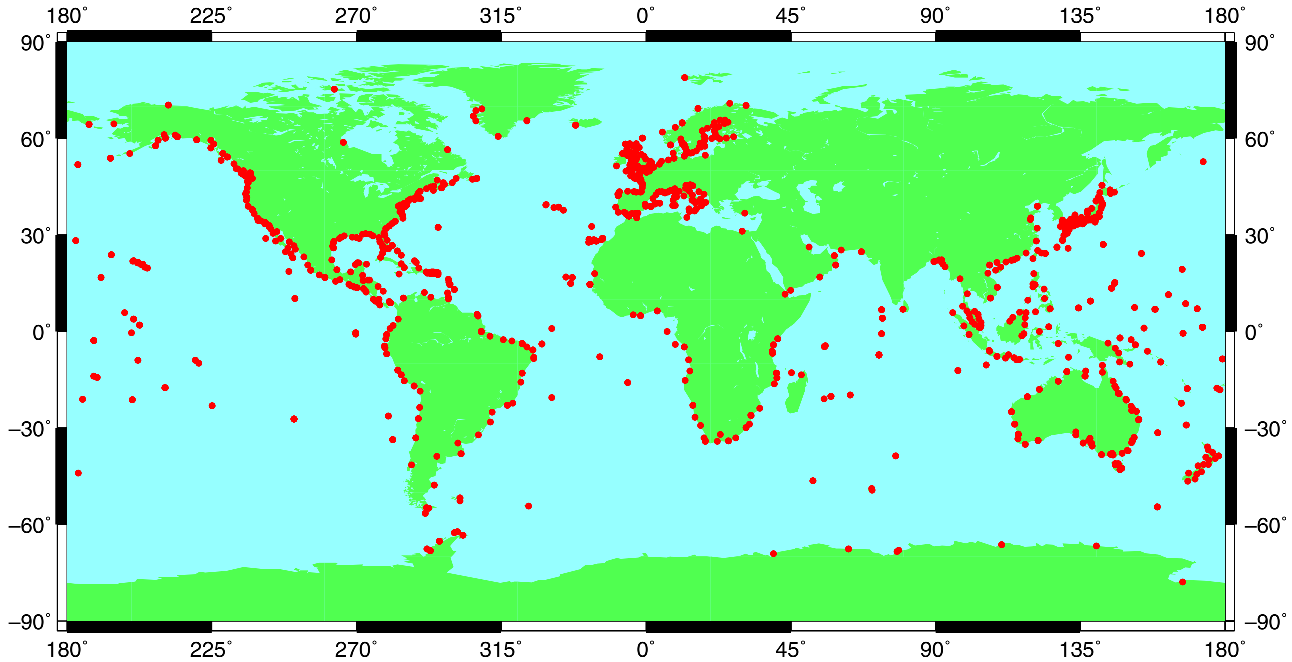

Figure 2. Locations of stations with sea level information in the GESLA-2 dataset (1355 records with 39 151 station-years, this paper).

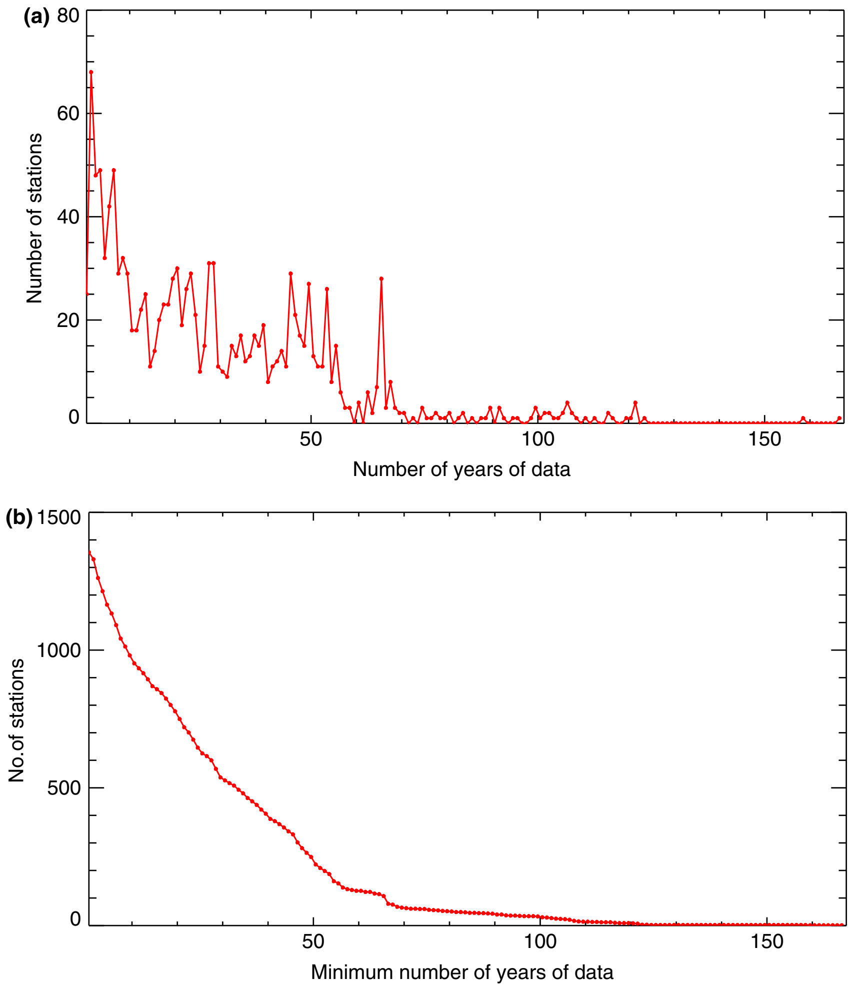

Figure 3. (a) Number of years of data in the records in GESLA-2. (b) Number of stations in GESLA-2 with at least the number of years of data indicated.

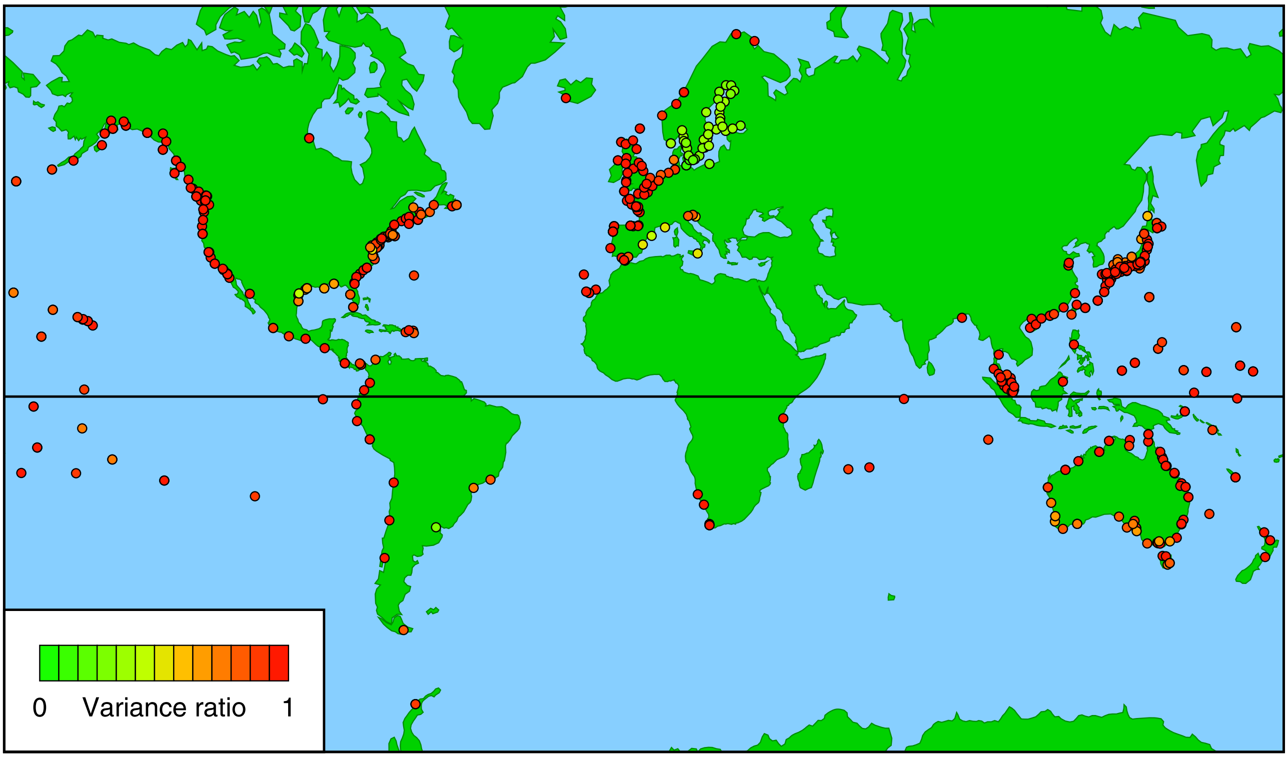

Figure 4. An example of application of GESLA-2 to sea level science, using data from each station that has at least 20 years of data, each of which is at least 80% complete. The figure shows the variance in sea level variability due to the ocean tide compared to the variance in the total observed sea level variability. Stations with ratios much less than one have small tides and/or large amounts of non-tidal variability in their records.

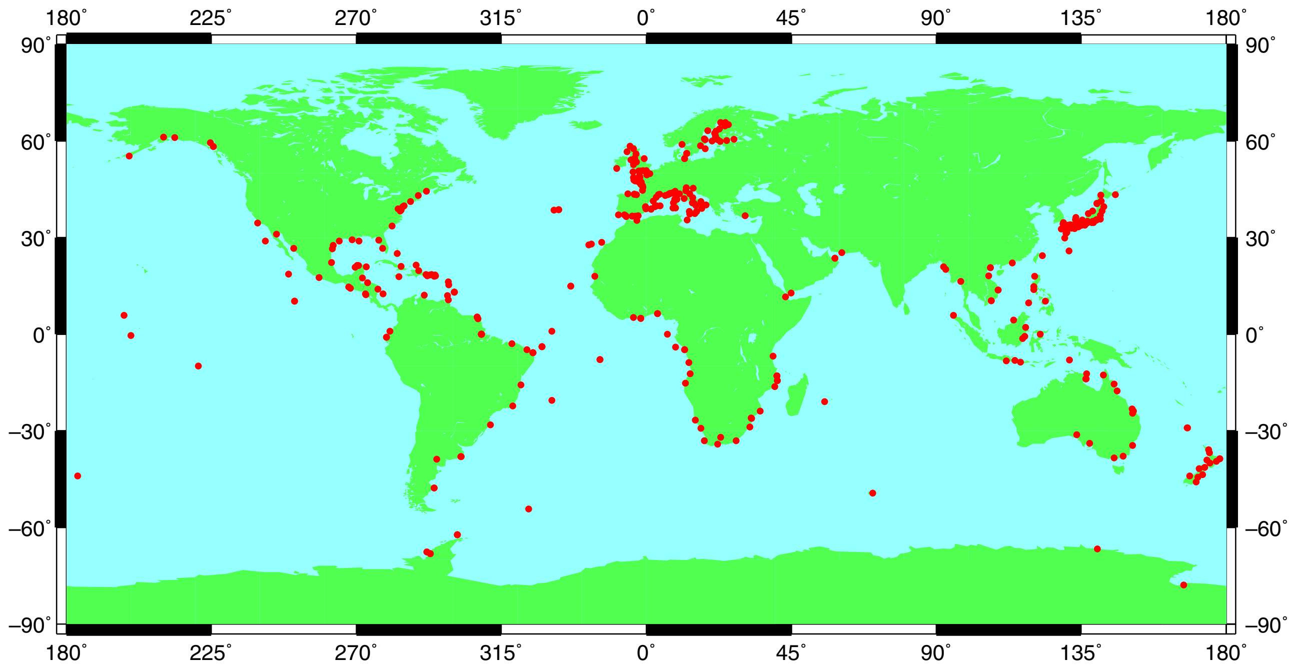

Figure 5. Stations in GESLA-2 that are more than 50 km from a station in GESLA-1.

where these are available. Subhourly data could be important to scientific analysis of processes such as tsunamis, meteotsunamis, and seiches that are not possible with hourly data.

The JASL dataset is an extremely useful product for oceanographic research and already has a good quasi-global coverage (Figure 1). However, it will be seen below that it is capable of being complemented by

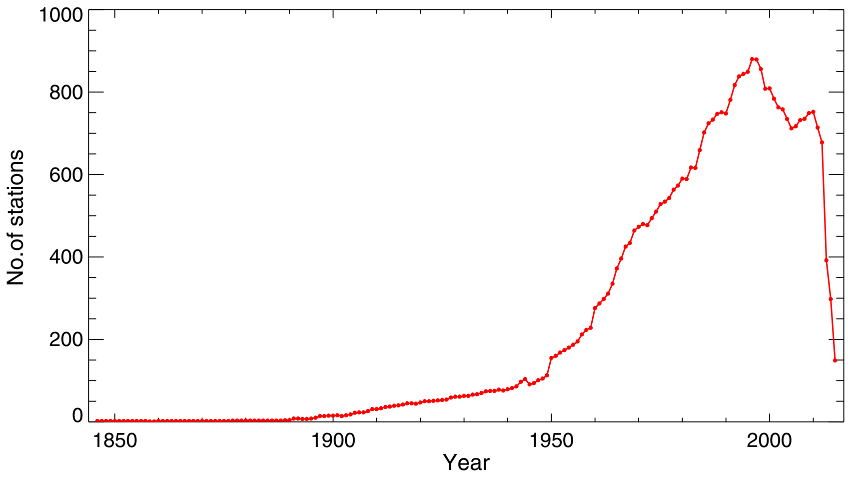

Figure 6. Number of stations in GESLA-2 with data in a particular year.

data from other, primarily national, sources to make a more complete dataset for scientific research.

The above provides a brief history of the origins of the main international databanks from which D-M sea level data can be obtained. We have not digressed into the history of the many other research programmes with sea level interests, such as the WCRP CLIVAR programme (now called Climate and Ocean: Variability, Predictability and Change), the Joint World Meteorological Organization (WMO)/IOC Commission for Oceanography and Marine Meteorology (JCOMM) sea level programme in the Pacific, the Integrated Global Ocean Services System (IGOSS) sea level project of the WMO and IOC, or the GCOS (Global Climate Observing System) of the WMO, IOC, the United Nations Environment Programme, and the International Council for Science. Each of these activities had sea level components that tended to overlap with GLOSS, but none of them had their own associated sea level databanks.

The essential point to be made in the context of the present paper is that none of the existing sea level databanks provides as complete as possible a quasi-global dataset, which we suggest is the D-M product that many researchers require. The following section describes how we have attempted to satisfy that requirement.

2. GESLA

The original GESLA dataset (GESLA-1) stemmed from the research needs for quasi-global information on the variability of extreme sea level events from year to year, primarily those that occur due to storm surges, and on the contributions of changes in MSL to variability in the extremes (Menéndez and Woodworth, 2010). It contained 21 197 station-years of data within 675 individual records. It was assembled from several sources:

1. Holdings of international sea level databanks mentioned above, primarily the UHSLC and GLOSS.
2. Contents of national databanks from which data were readily accessible from websites.
3. Contributions received from colleagues in the sea level community, several of whom had their own interests in extreme sea levels.

At the time (approximately 2008), there were fewer national websites (2) than now. In addition, in some cases, it was not clear from those websites whether data could be made available without conditions preventing their onward distribution to other users. Such conditions are understandable when data are subject to periodic updating by the authority that owns the data, which would result in the authority being reluctant to see a possibly older version of the data made available from another source. Nevertheless, there was usually an appreciation by most authorities contacted that this reluctance had to be overcome if the aim of assembling a quasi-global sea level dataset was to be achieved.

The developers of GESLA-1 did not keep detailed paper trails concerning whether data could be redistributed to other users. Consequently, the combined dataset was not made available publicly and was provided only to colleagues who we knew could be trusted not to circulate it further. This was an unsatisfactory situation which we have tried to address more rigorously for GESLA-2, as described below.

Approximately a dozen publications, concerning the science of extreme sea level variability and ocean tides and applications to coastal engineering, were based on GESLA-1; a list may be obtained from http://www.gesla.org. However, it gradually became evident that the dataset required updating to include nearly a decade of extra information, and to extend its coverage to previously under-represented regions. This became the GESLA-2 dataset released in early 2016.

Figure 2 shows that GESLA-2 has a reasonable geographical distribution, that is superficially similar to the distribution of Figure 1, although in fact with many more stations. It is planned to add other data in the future as they become available. The dataset presently contains 39 151 station-years of information from 1355 station records, with some stations having alternative versions of the records provided from different sources. The average record length is 29 years, although the actual number of years varies from only 1 at several short-lived sites, to 167 in the case of Brest, France (Figure 3(a)).

Figure 3(b) presents the same information, but showing instead the number of records in the dataset that have at least the number of years of data indicated. The long records in the extended tail with more than several decades of data will be of greatest interest to climate studies. However, even shorter records (say 10–20 years of data) can have application to studies in coastal engineering (e.g. Hunter, 2012; Hunter *et al.*, 2016) and sea level science (e.g. Figure 4).

Table 1. Example of a GESLA-2 data file (unalaska-9462620-noaa-usa) containing a header followed by the 'verified hourly sea level values' from NOAA in a simple column format; see http://www.gesla.org for a full description of the format.

Format version 3.0	Web: http://gesla.org Email: gesla.help@gmail.com
Site name	Unalaska
Country	United States
Contributor	NOAA (Downloaded from website)
Latitude	53.8800
Longitude	−166.5370
Coordinate system	Unspecified
Start date/time	1982/01/01 11:00:00
End date/time	2015/02/28 23:00:00
Time zone hours	0
Datum information:	NOAA Station Datum
Instrument	Unspecified
Precision	0.001 (m)
Null value	−99.9999
Creation date	UTC 2016/03/16
Column 1	Date yyyy/mm/dd
Column 2	Time hh:mm:ss
Column 3	Observed sea level (m)
Column 4	Observed sea level QC flag
Column 5	Used-in-extremes-analysis flag (1 = used, 0 = not used)
Quality-control (QC) flags	
0	No quality control
1	Correct value
2	Interpolated value
3	Doubtful value
4	Isolated spike or wrong value
5	Missing value
1982/01/01 11:00:00	0.9390 1 1
1982/01/01 12:00:00	0.8470 1 1
1982/01/01 13:00:00	0.8470 1 1
1982/01/01 14:00:00	0.9080 1 1
1982/01/01 15:00:00	1.0000 1 1
1982/01/01 16:00:00	1.2130 1 1
1982/01/01 17:00:00	1.3960 1 1
1982/01/01 18:00:00	1.6090 1 1
1982/01/01 19:00:00	1.7310 1 1
1982/01/01 20:00:00	1.8230 1 1
1982/01/01 21:00:00	1.7920 1 1
1982/01/01 22:00:00	1.7430 1 1
1982/01/01 23:00:00	1.6640 1 1
1982/01/02 00:00:00	1.5240 1 1
1982/01/02 01:00:00	1.4200 1 1
<Followed by data to 2015>	

Of course, the fact that GESLA-2 has twice as many station-years as GESLA-1 may be explained partly by many records being almost a decade longer. However, the new dataset also has a better geographical coverage as shown by the 'new regions' in Figure 5, defined by stations in the new dataset located more than 50 km from any station in GESLA-1. For example, major improvements can be seen to have been made for the Mediterranean and Baltic seas, Japan, New Zealand, and the African coastline south of the equator.

Most of the sea level measurements in GESLA-2 were made during the second half of the twentieth century (Figure 6). This period saw an expansion of national sea level networks and those of the oceanographic research programmes mentioned above. In addition, electronic data loggers were introduced instead of paper chart recorders leading to larger data streams. As a result, although there are some interesting individual long records that deserve study, Figure 6 demonstrates that the most globally representative analyses of sea level variability with GESLA-2 will be those that focus on the period since about 1970.

All the tide gauge data in GESLA-2 have hourly or more frequent sampling. For example, those provided by JASL/UHSLC have hourly sampling, as explained above. The basic data from the US National Atmospheric and Oceanic Administration (NOAA) are 6-min values but, instead of using a large number of big files, for GESLA-2 purposes, we instead settled on their readily available 'verified hourly values'. Most UK records are also hourly values up to the 1990s, and 15-min values thereafter. Records from some other sources may have different sampling, and records should be inspected individually if sampling considerations are considered critical to an analysis.

The records in GESLA-2 will have had some form of quality control undertaken by the data providers. However, the extent to which that control will have been undertaken will inevitably vary between providers and probably with time. Large tsunami signals will probably have been removed from, or flagged in, the records, but some small signals will inevitably remain (the website contains some information on possible tsunami signals in GESLA records). In most cases, no further quality control has been made beyond that already undertaken by the data providers.

GESLA-2 data may be obtained from http://www.gesla.org. The website also contains the file format description and other information. The text files contain headers with several lines of metadata followed by the data itself in a simple column format (Table 1). Contributors to the dataset are given in Table 2, which shows how it is divided into 27 ‘public’ and three ‘private’ subsets. Although there are many individual contributions, well over a quarter of the station-years are provided by the research quality dataset of UHSLC. Each subset was provided on the understanding that it can be copied readily to other interested users, can be copied subject to a firm acknowledgement to the original data owner, or cannot be copied at all. In practice, the majority is publically available but, for access to the ‘private’ subsets, an interested user should follow a procedure explained on the website.

GESLA-2 data can also been obtained from the BODC data portal through the digital object identifier given above.

3. Discussion

It is clear that there is a scientific and engineering requirement for datasets of D-M sea level information, and we have explained how a number of international databanks of D-M sea level data came about. D-M data from the UHSLC have been used extensively in many studies of sea level variability, especially those to do with the El Niño Southern Oscillation (ENSO) in the Pacific and with regard to calibration of satellite altimeter information, and the UHSLC has extended its historical regional remit to other ocean areas. We believe that data from the GLOSS D-M centre at BODC are used much less, and in fact, their main application has probably been their inclusion in GESLA. The databanks of the European Sea Level Service (ESEAS), Mediterranean GLOSS (MedGLOSS), and the Southern Ocean Sea Level Centre (SOSLC) were all short-lived for various reasons.

None of these databanks have provided a global D-M dataset such as GESLA, which we believe is what most researchers need, and from which the most spatially complete pictures of sea level change can be

Table 2. ‘Public’ and ‘private’ contributions to GESLA-2.

	Right-hand part of filename <country>-<contributor>	No. stations	No. station-years	Source
Public				
1	glossdm-bodc	191	3380	GLOSS Delayed Mode data copied from GESLA-1
2	*-uhslc	679	15 990	From uhslc.soest.hawaii.edu
3	japan-jma	80	3072	From Japan Meteorological Agency
4	uk-bodc	46	1627	From http://www.bodc.ac.uk
5	usa-noaa	73	3398	From opendap.co-ops.nos.noaa.gov
6	france_med-refmar	14	216	From refmar.shom.fr – acknowledgement needed
7	spain-pde	31	460	From Puertos del Estado, Spain
8	canada-meds	26	2017	From Marine Environmental Data Service, Canada
9	egypt-noc	1	20	Alexandria data processed by NOC, UK
10	spain-ieo	10	609	From Instituto Espanol de Oceanografica, Spain
11	italy-idromare	25	557	From idromare, Italy
12	turkey-eseas	1	14	Copied from GESLA-1
13	france-refmar	29	1081	From refmar.shom.fr - acknowledgement needed
14	uk-noc	5	75	From http://www.ntslf.ac.uk
15	sweden-smhi	30	1185	From SMHI, Sweden – acknowledgement needed.
16	spain_atlantic-ieo	3	204	From Instituto Espanol de Oceanografica, Spain
17	germany-bsh	1	99	From Federal Maritime and Hydrographic Agency, Germany
18	finland-fmi	13	598	From Finnish Meteorological Institute – acknowledgement needed
19	nl-rws	3	135	From Rijkswaterstaat Netherlands
20	croatia-eseas	3	7	Copied from GESLA-1
21	denmark-dmi	3	310	From http://www.dmi.dk/laer-om/generelt/dmi-publikationer/2013/
22	norway-statkart	6	280	From Norwegian Hydrographic Service
23	iceland-coastguard	1	45	From Icelandic Coastguard Service
24	italy-itt	1	43	From Istituto Talassographico di Trieste
25	italy-comune_venezia	1	32	From Venice Commune
26	uk+ukraine-noc	1	31	Data from the Ukraine Vernadsky base processed by NOC, UK
27	poland-eseas	1	42	Copied from GESLA-1
Private				
28	australia-johnhunter	29	1310	Copied from GESLA-1, original data from National Tidal Centre
29	australia-national_tidal_centre	47	2271	From National Tidal Centre Australia
30	croatia-university_zagreb	1	40	From University of Zagreb

derived albeit in delayed mode (cf. Merrifield *et al.*, 2015 which is an example of a review of sea level changes in the previous year based primarily on fast mode data). It is somewhat surprising that an effort to assemble such a dataset was not made long before GESLA. However, we suggest now that GLOSS (or another sea level programme with global interests) should include the ongoing assembly of the dataset as one of its priorities, in addition to its main aim of ensuring the establishment of as complete a global tide gauge network as possible.

There are number of future improvements to the dataset that one can consider in looking towards a GESLA-3. For example, GESLA-2 contains no data from India, even though such data exist (e.g. Antony *et al.*, 2016), because Indian higher-frequency data are not allowed to be distributed to the international community; on the other hand, MSL data are made available via the PSMSL. Similarly, there are no data from Russia, while data from only a small number of stations in China are made available via UHSLC. South America could also be better represented. In some of these countries, considerations of national security or data ownership continue to obstruct international data exchange. In addition, there are records to be included from recent exercises in 'data archaeology' (Talke and Jay, 2013). Of course, one cannot hope to include information from all of the many tide gauges owned by port authorities, or located in estuaries and rivers, and, in our opinion, the emphasis should be focussed on obtaining data from as much of the open-ocean world coastline as possible and from agencies which can be relied upon to provide good information.

The construction of GESLA-1 and GESLA-2 benefited from major contributions by scientists who undertook the work of assembling the datasets as part of their own research, and who took advantage of their personal links with many data providers. There was no direct input from the main sea level data centres, other than the provision of data. However, the two scientists who provided the bulk of the construction effort are now retired; there is unlikely to be a GESLA-3 or GESLA-4 without either other scientists taking on the responsibility or the data centres accepting the role. We believe that the latter would be the best option and we call upon them to do that, preferably within the auspices of GLOSS, before the time comes for GESLA-2 to require a major update.

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References

ACCE. 2016. Sea level observations in Antarctica. Antarctic Climate Change and the Environment (ACCE) committee of the Scientific Committee on Antarctic Research (SCAR). Available from http://acce.scar.org/wiki/Sea_level_observations.

Antony C, Unnikrishnan AS, Woodworth PL. 2016. Evolution of extreme high waters along the east coast of India and at the head of the Bay of Bengal. *Global and Planetary Change* **140**: 59–67. doi:10.1016/j.gloplacha.2016.03.008.

Caldwell PC, Merrifield MA. 2015. Joint Archive for Sea Level (JASL). Data Report: October 2015. Joint Institute for Marine and Atmospheric Research. JIMAR Contribution No. 15-392. Data Report No. 24. Available from http://ilikai.soest.hawaii.edu/UHSLC/jasl/datrep/JASL2015DataReport.pdf. The JASL is archived at the National Oceanographic Data Center (http://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.nodc:0019568).

Holgate SJ, Matthews A, Woodworth PL, Rickards LJ, Tamisiea ME, Bradshaw E, Foden PR, Gordon KM, Jevrejeva S, Pugh J. 2013. New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research* **29**: 493–504. doi:10.2112/JCOASTRES-D-12-00175.1.

Hunter J. 2012. A simple technique for estimating an allowance for uncertain sea-level rise. *Climatic Change* **113**: 239–252. doi:10.1007/s10584-011-0332-1.

Hunter JR, Woodworth PL, Wahl T, Nicholls RJ. 2016. Using global tide gauge data to validate and improve the representation of extreme sea levels in flood impact studies. (Submitted for publication).

IOC. 1990. Global Sea Level Observing System (GLOSS) implementation plan. UNESCO/Intergovernmental Oceanographic Commission, Technical Series, No. 35, 90 pp.

IOC. 1997. Global Sea Level Observing System (GLOSS) implementation plan-1997. UNESCO/Intergovernmental Oceanographic Commission, Technical Series, No. 50, 91 pp. & Annexes.

IOC. 2012. Global Sea Level Observing System (GLOSS) Implementation Plan – 2012. UNESCO/Intergovernmental Oceanographic Commission, Technical Series, No. 100, 41 pp.

IOC. 2016. Manual on sea level measurement and interpretation. Volume V: Radar gauges. Intergovernmental Oceanographic Commission, Manuals & Guides, No 14. (in press).

Kilonsky B, Caldwell P. 1991. In the pursuit of high-quality sea level data. *Proceedings of IEEE OCEANS '91. Ocean Technologies and Opportunities in the Pacific for the 90's*, Vol. 2, 669-675.

McPhaden MJ, Busalacchi AJ, Cheney R, Dongey J-R, Gage KS, Halpern D, Ji M, Julian P, Meyers G, Mitchum

GT, Niiler PP, Picaut J, Reynolds RW, Smith N, Takeuchi K. 1998. The tropical ocean global atmosphere observing system: a decade of progress. *Journal of Geophysical Research* **103**: 14169–14240. doi:10.1029/97JC02906.

Menéndez M, Woodworth PL. 2010. Changes in extreme high water levels based on a quasi-global tide-gauge dataset. *Journal of Geophysical Research* **115**: C10011. doi:10.1029/2009JC005997.

Merrifield MA, Thompson P, Leuliette E, Mitchum GT, Chambers DP, Jevrejeva S, Nerem RS, Menéndez M, Sweet W, Hamlington BD, Marra JJ. 2015. Sea level variability and change, in State of the Climate in 2014. In *Special Supplement to the Bulletin of the American Meteorological Society* 96: No. 7. Blunden J and Arndt DS (eds), S82–S85, doi:10.1175/2015BAMSStateoftheClimate.1.

Pugh D, Woodworth P. 2014. *Sea-level science: Understanding tides, surges, tsunamis and mean sea-level changes*. Cambridge University Press: Cambridge, 395 pp.

Spencer R, Foden PR, McGarry C, Harrison AJ, Vassie JM, Baker TF, Smithson MJ, Harangozo SA, Woodworth PL. 1993. The ACCLAIM programme in the South Atlantic and Southern Oceans. *International Hydrographic Review* **70**: 7–21.

Talke SA, Jay DA. 2013. Nineteenth century North American and Pacific tidal data: lost or just forgotten? *Journal of Coastal Research* **29**: 118–127. doi:10.2112/JCOASTRES-D-12-00181.1.

Testut L, Calzas M, Guillot A, Guillerm C, Téchiné P, Drezen C, Fichen L. 2012. ROSAME: bientôt 20 ans d'observation *in situ* du niveau de la mer dans l'océan austral. Comité National Français des Recherches Arctiques et Antarctiques - 8èmes Journées Scientifiques, Plouzané, 10-11 May 2012. Available from http://www.legos.obs-mip.fr/observations/rosame/documents/testut_cnfra_plouzane_proceeding_2012.pdf.

Wessel P, Smith WHF. 1998. New, improved version of Generic Mapping Tools released. *Eos, Transactions American Geophysical Union* **79**: 579.

Woodworth PL, Le Provost C, Rickards LJ, Mitchum GT, Merrifield M. 2002. A review of sea-level research from tide gauges during the World Ocean Circulation Experiment. *Oceanography and Marine Biology: An Annual Review* **40**: 1–35.

Woodworth PL, Hibbert A. 2015. Sea-level monitoring in the British Overseas Territories. *Journal of Operational Oceanography* **8**: 123–132. doi:10.1080/1755876X.2015.1087188.

Woodworth PL, Pugh DT, Plater AJ. 2015. Sea-level measurements from tide gauges. Chapter 35. In *Handbook of Sea-Level Research*, 1st ed. Shennan I, Long AJ and Horton BP. John Wiley & Sons: Chichester; 557–574 600 pp.

Woodworth PL, Hunter JR, Marcos MM, Caldwell PC, Menendez M, Haigh ID. 2016. GESLA (Global Extreme Sea Level Analysis) high frequency sea level dataset. British Oceanographic Data Centre – Natural Environment Research Council, UK, doi:10.5285/3b602f74-8374-1e90-e053-6c86abc08d39.