



GESLA Version 4: Further Enhancements to the Global Higher-Frequency Sea-Level Dataset

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Abstract. This paper presents GESLA-4, the latest major update to the quasi-global, higher-frequency sea-level dataset known as GESLA (Global Extreme Sea Level Analysis). Since its first release in 2009, GESLA has become a widely used observational resource for investigating tides, storm surges, extreme sea levels, and other coastal and oceanographic processes, supporting numerous published studies and major national and international assessments, including assessment reports of the Intergovernmental Panel on Climate Change. GESLA-4 represents a substantial expansion of the dataset, containing 136,069 station-years of observations across 6,682 records obtained from 43 international, national, and regional data sources. This represents an increase of 45,048 station-years and 1,563 records relative to GESLA-3. In addition to extending existing records and incorporating new data sources, GESLA-4 includes improvements to data processing and consistency, including a systematic review of record time zones. Data accessibility has also been enhanced through programmatic access via an Environmental Research Division's Data Access Program (ERDDAP) server and direct download links for individual stations via Amazon Web Services. This paper describes the assembly, processing, format and accessibility of GESLA-4, and also examines how the dataset has evolved across its four releases since 2009, and reviews how its scientific use has grown and diversified. GESLA-4 provides an extensive and readily accessible observational resource for investigating coastal sea levels, their variability and extremes, and their response to a changing climate.



1 Introduction

Sea-level observations are fundamental to understanding coastal and oceanographic processes and to managing the growing risks faced by coastal communities from flooding, erosion, saltwater intrusion and other coastal hazards. Long observational records provide the basis for detecting and understanding changes in mean sea level, one of the clearest indicators of climate change, while higher-frequency measurements are essential for resolving tides, storm surges, extreme sea levels and their interactions (Menéndez and Woodworth, 2010; Arns et al., 2020; Palmer et al., 2024). Such observations underpin coastal flood-risk assessments, the design and operation of coastal infrastructure and flood defences, and the development and validation of numerical models used for forecasting, reanalysis and climate projections (Oppenheimer et al., 2019; Muis et al., 2020; Chaigneau et al., 2022). Increasingly, large collections of observations are also being used to train and evaluate data-driven and machine-learning approaches to predicting coastal water levels and extremes (Tadesse et al., 2020; Tiggeloven et al., 2021; Nagaraj et al., 2025; Amores et al., 2026). Sea-level measurements also have applications extending well beyond coastal hazards. They are used to investigate tidal variability and ocean dynamics (Devlin et al., 2019; Haigh et al., 2020; Ray, 2020; Camargo et al., 2024), establish vertical and tidal datums (Woodworth, 2017; Palmer et al., 2023; Hart-Davis et al., 2026), support hydrographic surveying and nautical charting (Feng et al., 2023; Fu et al., 2025), and provide independent observations for evaluating satellite altimetry and regional and global ocean models (Piccioni et al., 2018; Oelsmann et al., 2021; Passaro and Juhl, 2023; Zhang et al., 2023; Quadrado et al., 2026). Within estuaries and deltas, tidal observations provide insights into local river flow and wind effects, the effects of dredging, reclamation, and other bathymetric modifications, and the influence of coastal and watershed management practices (e.g., Moftakhari et al., 2013; Baranes et al., 2023; Beemster et al., 2026). The value of these observations increases substantially when records from many locations can be brought together in a consistent format.

The international framework responsible for coordinating the collection and exchange of in situ sea-level observations is the Global Sea Level Observing System (GLOSS; <https://gloss-sealevel.org>), established by the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). GLOSS is supported by several international data centres that provide complementary sea-level data streams at different temporal resolutions and levels of processing. For studies of long-term sea-level change, the Permanent Service for Mean Sea Level (PSMSL; <https://psmsl.org>; Holgate et al., 2013) has assembled and distributed quality-controlled monthly and annual mean sea-level records since 1933. These records provide a cornerstone of research into multi-decadal to centennial changes in mean sea level. In contrast, studies of tides, storm surges, extreme sea levels, tsunamis and other processes operating at shorter timescales require higher-frequency observations, here defined as measurements at hourly or sub-hourly resolution. Several GLOSS data centres provide access to such observations. The University of Hawaii Sea Level Center (UHSLC) operates the GLOSS Fast Delivery Center and hosts the Joint Archive for Sea Level, which provides quality-controlled hourly sea-level observations (Caldwell et al., 2015). The British Oceanographic Data Centre maintains the GLOSS delayed-mode archive of high-frequency observations, while the IOC Sea Level Station Monitoring Facility, hosted by the Flanders Marine



65 Institute, provides access to near-real-time observations. In addition, Système d’Observation du Niveau des Eaux Littorales (SONEL) serves as the GLOSS data centre for Global Navigation Satellite System observations at or near tide gauges, enabling vertical land motion to be quantified alongside relative sea-level change.

Despite these international efforts, a much larger volume of higher-frequency sea-level observations is collected by national, regional and local monitoring organisations. These records remain distributed across numerous data portals and services, using different data formats, metadata conventions, sampling intervals, datum information and quality-control procedures, making their combined use challenging. The 2026 GLOSS Implementation Plan (IOC-UNESCO, 2026) identifies improved integration and access to sea-level observations as a major priority. GLOSS data centres are developing a Unified Data Portal based on interconnected ERDDAP servers, providing a centralised interface to curated data from designated GLOSS stations while retaining the existing distributed data-centre infrastructure. This development is accompanied by efforts to harmonise metadata, terminology, processing levels and quality-control information across GLOSS data centres, thereby improving the discoverability and interoperability of global sea-level observations.

The Global Extreme Sea Level Analysis (GESLA) dataset was established to address the broader challenge of bringing together higher-frequency sea-level observations from multiple international, national and regional sources and distributing them in a common format. Rather than replacing the important archives maintained by individual data providers, GESLA provides an additional layer of aggregation and harmonisation that allows observations from these disparate sources to be more readily used together. GESLA therefore complements the curated GLOSS data streams by incorporating a much broader set of current and historical tide-gauge records. This role is formally recognised in the 2026 GLOSS Implementation Plan, which identifies GESLA as a GLOSS aggregated dataset and distinguishes it from curated datasets based on designated GLOSS Reference Stations. GESLA will continue to be distributed through its own website and (with this release) a dedicated Environmental Research Division's Data Access Program (ERDDAP) server and Amazon Web Services (AWS), complementing the developing GLOSS Data Portal. The resulting spatial coverage and number of records are particularly valuable for applications including analyses of tides, storm surges, extreme sea levels, compound flooding, model evaluation and, increasingly, machine-learning applications.

Since its establishment in 2009, GESLA has grown into a widely used community resource (as highlighted in Section 3). Here, we present GESLA Version 4.1, the latest and largest release of the dataset, published in July 2026 following the initial release of GESLA-4.0 in July 2025. Previous generations of GESLA (GESLA-1, GESLA-2 and GESLA-3) each comprised a single release; however, as the dataset continues to grow and data acquisition becomes increasingly automated, we plan to update GESLA more regularly, ideally annually. We have therefore introduced sub-version numbering (e.g., GESLA-4.0, GESLA-4.1) to distinguish successive updates within each major generation of the dataset. For simplicity, throughout the remainder of this paper we refer to the current GESLA-4.1 release simply as GESLA-4, unless distinction between sub-versions is necessary. Between GESLA-4.0 and GESLA-4.1, additional records were incorporated, existing records were updated, and several aspects of the processing were revisited, including a systematic review and correction of record time zones. Data accessibility has also been substantially enhanced through programmatic access to GESLA via an



ERDDAP server hosted by the UHSLC and direct download links for individual stations via AWS. Together, these
developments improve the consistency, currency and accessibility of the expanding GESLA archive and facilitate its
integration into automated and reproducible scientific workflows.

This paper describes the data sources incorporated into GESLA-4, the procedures used to process and harmonise the
observations, the resulting spatial and temporal coverage, licensing and data-access arrangements, and progress towards the
FAIR (Findable, Accessible, Interoperable, and Reusable) data principles (Section 2). We then take the opportunity, seventeen
years after GESLA was first assembled, to examine how the dataset has evolved across its four releases and to briefly review
how its scientific use has developed and diversified (Section 3). Finally, we discuss remaining challenges and priorities for
future development of GESLA (Section 4).

2 Data description and development

In this section, we describe the GESLA data sources, record locations, and number of years of data (Section 2.1), outline the
data processing and format (Section 2.2), describe the usage licences (Section 2.3), and discuss the dataset with regard to the
established FAIR data principles (Section 2.4).

2.1 Data sources

For GESLA-4, we assembled higher-frequency hourly sea-level observations from the 43 international and national data
providers listed in Table 1. Aggregated statistics for the data from each provider, including record lengths and the start and
end dates, are shown in Table 2, and are ordered according to the total number of years of data contributed. Consistent with
previous versions of GESLA, a record refers to a sea-level time series from a particular tide-gauge station and provider, and
its length is expressed as the number of calendar years containing at least one observation. A station may therefore be
represented by more than one record, either because data are available from multiple providers or because a time series has
been divided following changes in datum, instrumentation, or station location. Some locations may have overlapping time
series from independent gauges deployed by different agencies. For example, Rio Vista in California has independent
measurements from the US Geological Survey and California Department of Water Resources.

Where possible, we retrieved updated versions of the complete records from the sources used for GESLA-3,
incorporating additional years of observations as well as any subsequent revisions made by the data providers. These
established sources and their acquisition are described in Haigh et al. (2023) and are not repeated here. GESLA-4 also
incorporates records from seven new data sources, which are described below (see also Table 1).



Table 1: Information on data providers, licences and data use. Grey shading indicates new data sources not in GESLA-3.

No.	Abbrev. name	Full name	Website	Region/Country	Download method	Licence	Use
1	UHSLC_RQ	University of Hawaii Sea Level Center – Research Quality	https://uhslc.soest.hawaii.edu	Global	Downloaded each record automatically via API (ERDDAP server)	Specified on website: https://uhslc.soest.hawaii.edu/erddap/tabledap/global_daily_rqds.html	Research and consultancy
2	NOAA	National Oceanic and Atmospheric Administration	https://api.tidesandcurrent.s.noaa.gov/api/prod/	United States of America	Downloaded each record automatically via API	Unspecified	Research and consultancy
3	CMEMS	Copernicus Marine Environment Monitoring Service	https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=INSITU_GLO_NRT_OBSERVATIONS_013_030	Europe	Download NetCDF files from FTP site	Specified in NetCDF data files	Research (for consultancy contact data owners directly)
4	UHSLC_FD	University of Hawaii Sea Level Center – Fast Delivery	https://uhslc.soest.hawaii.edu	Global	Downloaded each record automatically via API (ERDDAP server)	Specified on website: https://uhslc.soest.hawaii.edu/erddap/tabledap/global_daily_rqds.html	Research and consultancy
5	MEDS	Marine Environmental Data Section	https://isdmgdsi.gc.ca/isdmgdsi/twl-mne/inventory-inventaire/index-eng.htm	Canada	Downloaded each record manually from website (in 10-year blocks)	Specified on website: https://www.qc.dfo-mpo.gc.ca/tides/en/licence-agreement	Research and consultancy
6	USGS	United States Geological Survey	http://waterdata.usgs.gov/nwis/uv	United States of America	Downloaded each record manually from website	Unspecified	Research and consultancy
7	RWS	Rijkswaterstaat	https://rijkswaterstaatdata.nl/waterdata	The Netherlands	Downloaded each record automatically via API	Specified on website: https://rijkswaterstaatdata.nl/waterdata	Research and consultancy
8	BOM	Bureau of Meteorology	http://www.bom.gov.au/oceanography/projects/absimp/absimp.shtml	Australia and Pacific Islands	Obtained directly from BOM	Unspecified	Research and consultancy
9	CRMS	Louisiana Coastwide Reference Monitoring System	https://www.lacoast.gov/crms/Home.aspx	Mississippi Delta (United States of America)	Downloaded each record manually from website	Unspecified	Research and consultancy
10	RWS_HIST	Rijkswaterstaat – Historic Data	https://opendap.deltares.nl/thredds/catalog/opendap/rijkswaterstaat/waterbase/27_Waterhoogte_in_cm_t.o.v._normaal_amsterdam_peil_in_oppervlaktewater/nc/catalog.html	The Netherlands	Downloaded each record manually from website	Unspecified	Research and consultancy
11	JODC_JMA	Japan Oceanographic Data Center, Japan Meteorological Agency	https://jdoss1.jodc.go.jp/vpage/tide.html	Japan	Downloaded each site manually from website (in 10-year blocks)	Specified on website: https://jdoss1.jodc.go.jp/vpage/tide.html	Research and consultancy



No.	Abbrev. name	Full name	Website	Region/Country	Download method	Licence	Use
12	WSV	Wasserstraßen- und Schifffahrtsverwaltung des Bundes (Federal Waterway and Shipping Administration)	https://pegelonline.wsv.de/gast/start	Germany	Downloaded each record manually from website	Specified on website: https://pegelonline.wsv.de/gast/nutzungsbedingungen Data Licence Germany – Zero – Version 2.0 (DL-DE Zero 2.0)	Research and consultancy
13	CDWR	California Department of Water Resources	https://cdec.water.ca.gov/	United States of America	Downloaded each record manually from website	Unspecified	Research and consultancy
14	REFMAR	Réseaux de référence des observations marégraphiques (Reference networks for tidal observations)	http://refmar.shom.fr/en	France	Downloaded each record manually from website	Unspecified	Research and consultancy
15	SMHI	Swedish Meteorological and Hydrological Institute	https://www.smhi.se/data/oceanografi/ladda-ner-oceanografiska-observationer/#param=sealevelMinutes,stations=all	Sweden	Manually downloaded each record from website.	http://www.smhi.se/data/op-pna-data/information-om-op-pna-data/villkor-for-anvandning-1.30622	Research and consultancy
16	BODC	British Oceanographic Data Centre	https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/	United Kingdom of Great Britain and Northern Ireland	Downloaded each record manually from website	https://www.nationalarchives.gov.uk/doc/open-government-licence/version/2/	Research and consultancy
17	JODC_JCG	Japan Oceanographic Data Center, Japan Coast Guard	https://jdoss1.jodc.go.jp/vpage/tide.html	Japan, Antarctica	Downloaded each record manually from website	Specified on website: https://jdoss1.jodc.go.jp/vpage/tide.html	Research and consultancy
18	NHS	Norwegian Hydrographic Service	http://api.sehavniva.no/tideapi_en.html	Norway	Downloaded each record automatically via API and combined with historic data obtained directly	https://creativecommons.org/licenses/by/4.0/deed.en	Research and consultancy
19	JODC_GIAJ	Japan Oceanographic Data Center, Geospatial Information Authority of Japan	https://jdoss1.jodc.go.jp/vpage/tide.html	Japan	Downloaded each record manually from website	Specified on website: https://jdoss1.jodc.go.jp/vpage/tide.html	Research and consultancy
20	SFWMD	South Florida Water Management District	https://www.sfwmd.gov/science-data/dbhydro	United States of America	Downloaded each record manually from website	Unspecified	Research and consultancy



No.	Abbrev. name	Full name	Website	Region/Country	Download method	Licence	Use
21	JODC_P AHB	Japan Oceanographic Data Center, Ports and Harbours Bureau	https://jdoss1.jodc.go.jp/vpage/tide.html	Japan	Downloaded each record manually from website	Specified on website: https://jdoss1.jodc.go.jp/vpage/tide.html	Research and consultancy
22	ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale (Higher Institute for Environmental Protection and Research)	https://mareografico.it	Italy	Downloaded each record manually from website	N/A	Research and consultancy
23	FMI	Finnish Meteorological Institute	https://en.ilmatietaenlaitos.fi/download-observations	Finland	Downloaded each record manually from website (in 15-year blocks)	https://en.ilmatietaenlaitos.fi/open-data-licence	Research and consultancy
24	IEO	Instituto Español de Oceanografía (Spanish Institute of Oceanography)	https://www.seadatanet.org	Spain	Downloaded each record manually from website	Unspecified	Research and consultancy
25	DA	Data Archaeology	N/A	United States of America, Spain, United Kingdom of Great Britain and Northern Ireland	Obtained directly from authors	N/A	Research and consultancy
26	UNAM_HIST	National Autonomous University of Mexico – Historical Data	http://www.mareografico.unam.mx/portal/ (website doesn't exist anymore)	Mexico	Downloaded each record manually from website	Specified on website http://www.mareografico.unam.mx/portal/	Research and consultancy
27	DMI	Danish Meteorological Institute	http://ocean.dmi.dk/english/index.php	Denmark	Data obtained directly	Unspecified	Research and consultancy
28	MI_C	Marine Institute (Coastal sites)	https://erddap.marine.ie/erddap/tabledap/IrishNationalTideGaugeNetwork.html	Ireland	Downloaded each record automatically via API (ERDDAP server)	https://creativecommons.org/licenses/by/4.0/	Research and consultancy
29	TTW	Toitū Te Whenua	https://www.linz.govt.nz/products-services/data/types-linz-data/sea-level-data/sea-level-data-downloads	New Zealand	Downloaded each record manually from website in yearly blocks	Creative Commons Attribution 3.0 NZ licence https://creativecommons.org/licenses/by/3.0/nz/	Research and consultancy



No.	Abbrev. name	Full name	Website	Region/Country	Download method	Licence	Use
30	BFG	Bundesanstalt für Gewässerkunde (Federal Institute of Hydrology)	https://www.bafg.de/EN/03_The_%20BfG/the_bf_g.html	Germany	Data obtained directly	Unspecified	Research and consultancy
31	HCT	Harris County, Texas	https://alert.hcfcdcontrail.org/list/	Texas, United States of America	Downloaded each record manually from website	Unspecified	Research and consultancy
32	CCO	Channel Coastal Observatory	https://coastalmonitoring.org/realtimedata/	United Kingdom of Great Britain and Northern Ireland	Downloaded each record manually from website	https://www.nationalarchives.gov.uk/doc/open-government-licence/version/2/	Research and consultancy
33	UNAM	National Autonomous University of Mexico	https://www.unaminternacional.unam.mx/en/unam	Mexico	Data obtained directly	Unspecified	Research and consultancy
34	NCDEM	North Carolina Department of Emergency Management	https://www.ncdps.gov/ncem	United States of America	Downloaded each record manually from website	Unspecified	Research and consultancy
35	NOC	National Oceanography Centre	https://noc.ac.uk	United Kingdom of Great Britain and Northern Ireland, Egypt, Ukraine	Data obtained directly	Unspecified	Research and consultancy
36	NWFW MD	Northwest Florida Water Management District	https://nwfwwater.com/Data-Publications/Hydrologic-Data/Active-Stations-Map	United States of America	Downloaded each record manually from website	Unspecified	Research and consultancy
37	UZ	University of Zagreb	https://www.pmf.unizg.hr/geof/en#	Croatia	Data obtained directly	Unspecified	Research (for consultancy contact data owners directly)



No.	Abbrev. name	Full name	Website	Region/Country	Download method	Licence	Use
38	CM	California Miscellaneous (Marin County/OneRain; Santa Barbara/OneRain; Santa Clara Valley; Water Authority; Napa County/OneRain; Water Authority; Santa Cruz/OneRain)	https://marin.onerain.com https://rain.cosbpw.net https://alert.valleywater.org https://napa.onerain.com https://santacruz.onerain.com	California, United States of America	Downloaded each record manually from website	Unspecified	Research and consultancy
39	MI_R	Marine Institute (River Sites)	https://erddap.marine.ie/erddap/tabledap/IrishNationalTideGaugeNetworkRiverGauges.html	Ireland	Automatically load in data using ERDDAP	https://creativecommons.org/licenses/by/4.0/	Research and consultancy
40	ESEAS	European Sea-Level Service	https://www.bodc.ac.uk/projects/data_management/european/eseas/	Poland, Turkey, Croatia	Copied from GESLA-2	Unspecified	Research and consultancy
41	ICG	Icelandic Coast Guard Hydrographic and Maritime Safety Department	http://www.lhg.is/english/about-us/	Iceland	Data obtained directly	Unspecified	Research and consultancy
42	CV	City of Venice, Tide Forecasts and Reporting Center	https://www.comune.venezia.it/node/6214	Italy	Downloaded manually from website	https://creativecommons.org/licenses/by-nc-sa/3.0/it/	Research (for consultancy contact data owners directly)
43	GLOSS	Global Sea Level Observing System	https://gloss-sealevel.org	Greenland	Copied from GESLA-2	Unspecified	Research and consultancy

130 In previous versions of GESLA, we included only the quality-controlled UHSLC “Research Quality” dataset (‘UHSLC_RQ’).
 Because the quality-control process is necessarily time-intensive, these records typically lag behind the most recent
 observations. At the time of compiling GESLA-4, ‘UHSLC_RQ’ data were available through to the end of 2024. To improve
 the temporal currency of GESLA-4, we additionally incorporated the UHSLC “Fast Delivery” dataset (‘UHSLC_FD’), which
 extends many stations with more recent observations, including data from 2025 and 2026, that have not yet undergone the full
 135 research quality assessment. Although there is substantial temporal overlap between ‘UHSLC_RQ’ and ‘UHSLC_FD’, the
 two products can be combined to provide longer and more up-to-date sea-level records.

In GESLA-3, sea-level data for the Netherlands were obtained for 124 Rijkswaterstaat tide-gauge sites through an
 OPeNDAP server maintained by Deltares. These records extended only to the end of 2018 and have not subsequently been
 updated. Rijkswaterstaat now provides up-to-date sea-level observations directly through an alternative Application



140 Programming Interface (API) (Table 1), from which we obtained records for 278 tide-gauge sites across the Netherlands. Because the spatial and temporal coverage of the historical and newly acquired records does not fully overlap, both datasets are retained in GESLA-4 to maximise record coverage. We refer to these as ‘RWS_HIST’, for the historical dataset obtained via Deltares, and ‘RWS’, for the newer dataset obtained directly from Rijkswaterstaat.

In GESLA-3, sea-level data for Mexico were obtained for 35 tide-gauge sites through the UNAM website (Table 1), with
 145 records extending to the end of 2018. As this website is no longer accessible, we contacted UNAM directly and obtained records from 50 tide-gauge sites covering the period 2019–2024. Because the spatial and temporal coverage of the historical and newly provided records does not fully overlap, both datasets are retained in GESLA-4 to maximise record coverage. We refer to these as ‘UNAM_HIST’, for the historical dataset previously obtained through the UNAM website, and ‘UNAM’, for the newer dataset provided directly by UNAM. Again, the two products can be combined to provide longer and more up-to-
 150 date sea-level records.

In GESLA-4, we have added new sea-level records from 21 tide-gauge sites in New Zealand, manually downloaded from the Toitū Te Whenua (TTW) website (Table 1). New Zealand’s sea-level monitoring network was established between March 2007 and July 2010, primarily to strengthen the country’s capability to monitor and respond to tsunami hazards. We also manually downloaded new sea-level records from three regional networks along the coasts of the United States. For
 155 Louisiana, records from 340 tide-gauge sites covering 2006–2025 were obtained from the Coastwide Reference Monitoring System (CRMS), a network established to assess the effectiveness of coastal restoration and protection projects across a range of wetland environments and spatial scales. In Texas, records from 17 sites covering 1987–2024 were obtained from the Harris County Flood Control District (HCT), whose monitoring network provides near-real-time water-level observations in bayous and major streams to support flood monitoring, warning, and emergency response. In California, records from 13 sites covering
 160 2014–2025 were obtained from several regional monitoring networks (CM - California Miscellaneous), including those operated in Santa Barbara, Napa, Marin, Santa Cruz and Santa Clara counties. These networks primarily support real-time hydrological monitoring, flood warning, and emergency response, with many of the observations distributed through the OneRain platform. As these networks include numerous riverine stations, for GESLA-4 we retained only sites exhibiting a clear diurnal inequality and spring-neap variability in water levels during at least several months of the year, indicating tidal
 165 influence. Records representing exclusively riverine water-level variability were removed.

Three data sources included in GESLA-3 have been substantially expanded (both in number and data length). The Copernicus Marine Environment Monitoring Service (CMEMS) dataset has increased from 590 records, comprising 9,753 station-years, in GESLA-3 to 717 records and 15,555 station-years in GESLA-4. A substantially larger number of German tide-gauge records are also now available through the Wasserstraßen- und Schifffahrtsverwaltung des Bundes (WSV - Federal
 170 Waterway and Shipping Administration) website (Table 1). We downloaded these additional records, retaining only stations exhibiting clear tidal variability, as many of the available gauges are located along rivers beyond the tidal limit. Consequently, the WSV dataset has increased from 66 records and 1,262 station-years in GESLA-3 to 142 records and 3,599 station-years in GESLA-4. Similarly, the United States Geological Survey (USGS) dataset was increased from 464 to 650 records with a



combined length of 8,065 station-years, an increase of 2,751 station-years since GESLA-3. These represent a combination of previously unidentified records and records from new gauges. The statistics for other providers increased for similar reasons (e.g., North Carolina Department of Emergency Management (NCDEM) increased from 10 to 37 gauges).

The number of records and station-years contributed by each of the 43 data sources is summarised in Table 2. In total, GESLA-4 contains 6,682 records comprising 136,069 station-years of observations, an increase of 1,563 records and 45,048 station-years relative to GESLA-3. Figure 1 shows the global distribution of records across the four versions of GESLA and illustrates the substantial expansion in spatial coverage since GESLA-1. This increase is examined in greater detail in Figure 2 for four regions where coverage has notably improved between GESLA-3 and GESLA-4: North America (Figure 2a), Europe (Figure 2b), Southeast Asia (Figure 2c) and New Zealand (Figure 2d). The final column of Table 2 lists the number of countries represented by each data source. GESLA-4 now contains records from 119 countries, five more than GESLA-3. The two UHSLC datasets provide by far the broadest geographical coverage, with ‘UHSLC_RQ’ and ‘UHSLC_FD’ containing records from 97 and 85 countries, respectively. Importantly, UHSLC contributions include 70 countries, and >60 Global South nations, not available from other GESLA sources, emphasising the continuing importance of UHSLC in providing the global coverage of GESLA. The spatial expansion between GESLA-3 and GESLA-4 is illustrated in Figure 3, which shows the locations of records in GESLA-4 that are more than 10 km from a record in GESLA-3. Figure 4 shows the distance (km) to the nearest GESLA-4 record, highlighting substantial observational gaps along several stretches of coastline, particularly in northern Russia and Siberia, parts of northern Canada and Greenland, sections of western and central Africa, and parts of the Antarctic coastline, where the nearest tide-gauge record can be several hundred kilometres away. The temporal characteristics of the GESLA-4 archive are summarised in Figure 5. Figure 5a shows the distribution of individual record lengths, while Figure 5b groups the records into different length classes. Figure 5c shows the distribution of record start dates, and Figure 5d shows the number of records containing observations in each year. The geographical distribution of records according to their length is shown in Figure 6, distinguishing records ranging from less than 5 station-years to more than 100 station-years. Figure 7 complements this by showing the geographical distribution of records according to their starting date, illustrating both the relatively small number of historical records extending back into the nineteenth century and the much greater spatial coverage provided by records established during the twentieth and twenty-first centuries.



200 **Table 2:** Number of records and years of data for each data source.

Number	Abbreviated name	No. of records	No. of years	No. records >100 years	No. records 50-100 years	No. records 20-50 years	No. records 10-20 years	No. records 5-10 years	No. records <5 years	Min year	Max year	No. of countries
1	UHSLC_RQ	692	18856	21	88	228	136	103	116	1846	2024	97
2	NOAA	1395	16426	20	111	125	88	83	968	1897	2026	1
3	CMEMS	717	15555	13	46	226	218	113	101	1821	2026	26
4	UHSLC_FD	322	12091	18	68	120	59	30	27	1846	2026	85
5	MEDS	868	9203	9	63	59	56	55	626	1895	2025	1
6	USGS	650	8065	0	0	50	341	136	123	1986	2025	1
7	RWS	278	7014	6	40	65	50	29	88	1800	2026	1
8	BOM	172	5960	2	31	105	29	4	1	1897	2025	14
9	CRMS	340	5929	0	0	52	257	29	2	2006	2025	1
10	RWS_HIST	124	4482	4	17	54	27	12	10	1800	2018	1
11	JODC_JMA	81	3826	0	54	16	9	2	0	1960	2024	1
12	WSV	142	3599	0	0	127	12	3	0	2000	2026	1
13	CDWR	132	3032	0	0	73	36	14	9	1982	2025	1
14	REFMAR	108	2833	2	14	30	45	8	9	1821	2026	1
15	SMHI	71	2690	7	16	6	33	4	5	1886	2026	1
16	BODC	46	2051	1	15	28	2	0	0	1915	2026	1
17	JODC_JCG	31	1790	0	22	9	0	0	0	1910	2025	2
18	NHS	24	1647	4	15	4	1	0	0	1914	2026	1
19	JODC_GIAJ	25	1502	0	20	5	0	0	0	1932	2023	1
20	SFWMD	43	1480	0	2	37	4	0	0	1970	2024	1
21	JODC_PAHB	70	1372	0	2	22	45	0	1	1961	2023	1
22	ISPRA	39	1108	0	0	26	10	0	3	1971	2026	1
23	FMI	14	727	0	12	1	1	0	0	1971	2026	1
24	IEO	12	725	0	10	1	1	0	0	1943	2016	1
25	DA	29	685	1	3	10	3	3	9	1855	2019	3
26	UNAM_HIST	35	663	0	2	14	6	4	9	1946	2018	1
27	DMI	3	349	2	1	0	0	0	0	1891	2026	1
28	MI_C	25	316	0	0	4	11	7	3	2006	2026	1
29	TTW	21	312	0	0	0	18	3	0	2007	2025	1
30	BFG	5	269	1	1	3	0	0	0	1917	2024	1
31	HCT	17	253	0	0	4	9	1	3	1987	2024	1
32	CCO	16	242	0	0	4	9	3	0	1996	2026	1
33	UNAM	50	189	0	0	0	0	0	50	2019	2024	1
34	NCDEM	37	181	0	0	0	3	14	20	2013	2025	1
35	NOC	7	137	0	0	3	4	0	0	1957	2018	3
36	NWFWMD	9	120	0	0	0	8	1	0	2000	2025	1
37	UZ	1	85	0	1	0	0	0	0	1929	2022	1
38	CM	13	74	0	0	0	2	6	5	2014	2025	1
39	MI_R	9	70	0	0	0	0	8	1	2018	2026	1
40	ESEAS	5	63	0	0	1	1	0	3	1935	2003	3
41	ICG	1	51	0	1	0	0	0	0	1970	2020	1
42	CV	1	41	0	0	1	0	0	0	1983	2023	1
43	GLOSS	2	6	0	0	0	0	0	2	1997	1999	1
-	Total	6682	136069	111	655	1513	1534	675	2194	1800	2026	119

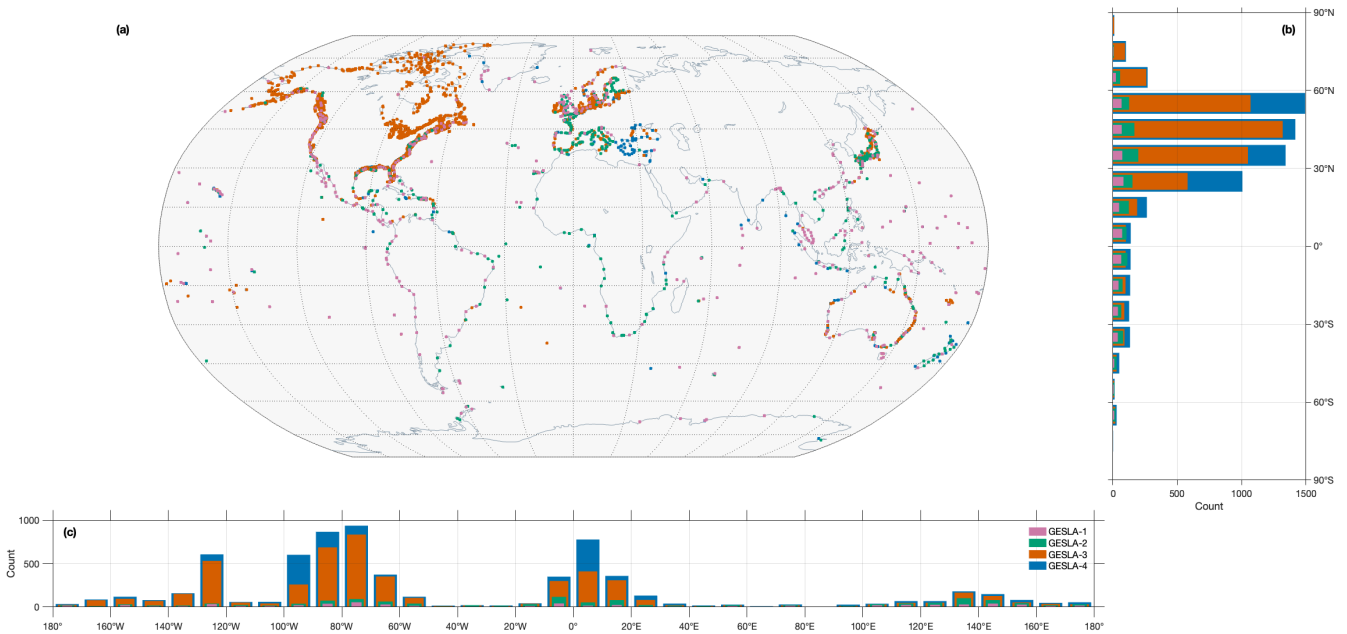
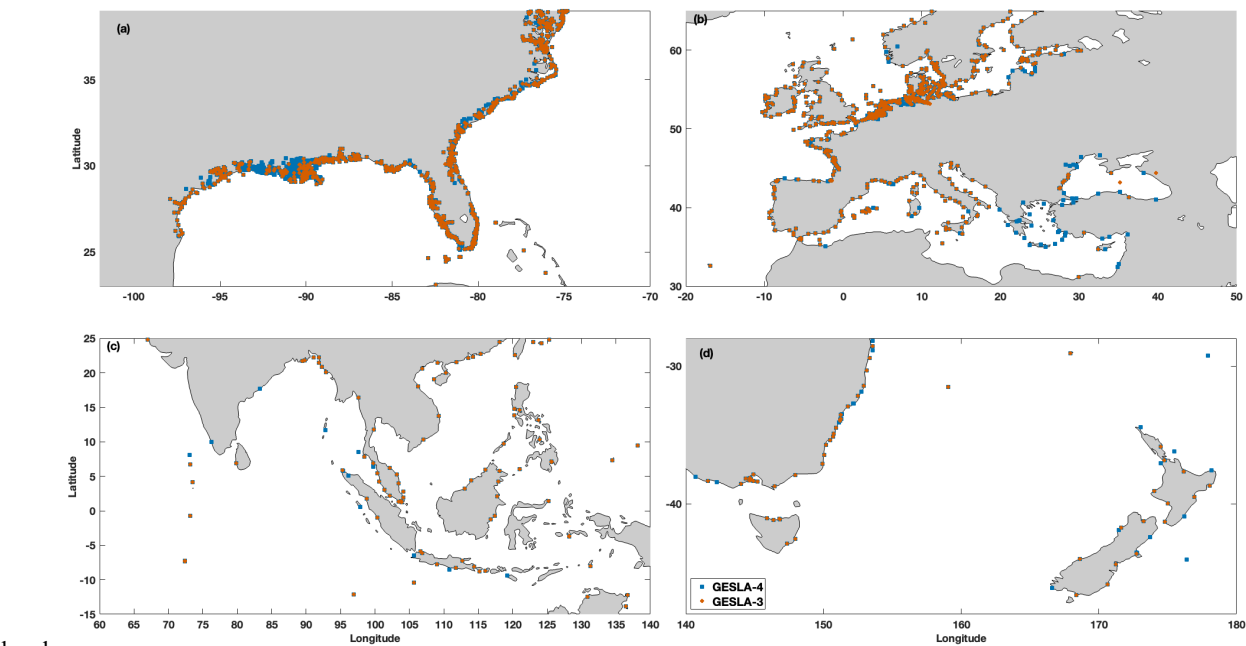


Figure 1: (a) Locations of the sea-level records in the four versions of GESLA and counts of sites in 10-degree (b) latitude and (c) longitude



bands.

Figure 2: Locations of the sea-level records in GESLA-4 and GESLA-3 for four example regions with increased coverage: (a) North America; (b) Europe; (c) Southeast Asia and (d) New Zealand. Note the GESLA-3 locations are also in GESLA-4. Note, we have overlaid GESLA-3 on top of GESLA-4, so where a GESLA-3 location is, there is also a GESLA-4 location.

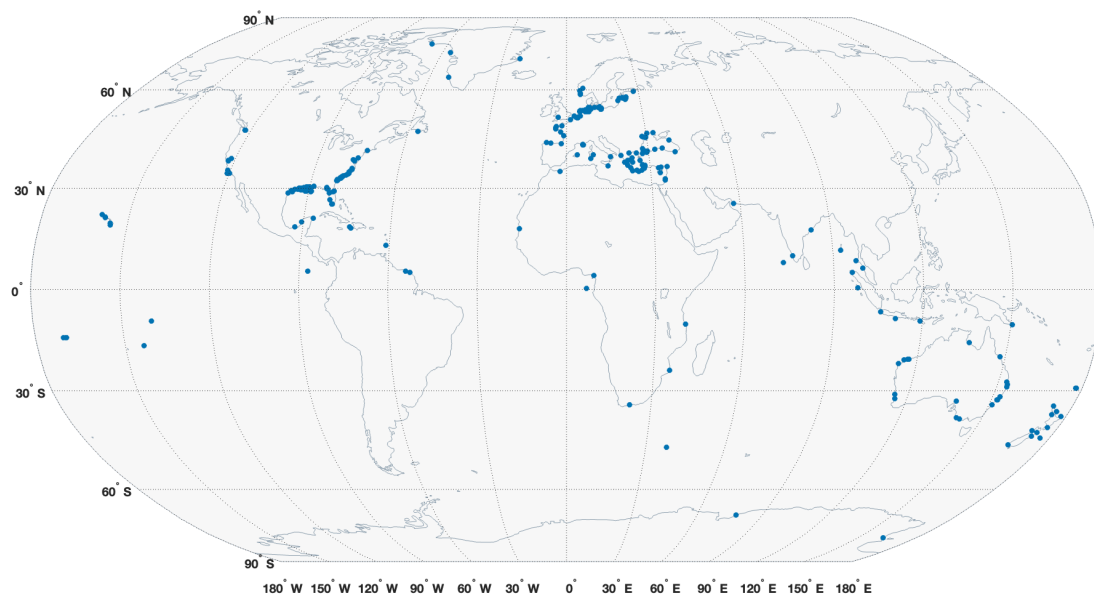


Figure 3: Locations of sea-level records in GESLA-4 that are more than 10 km from a record in GESLA-3.

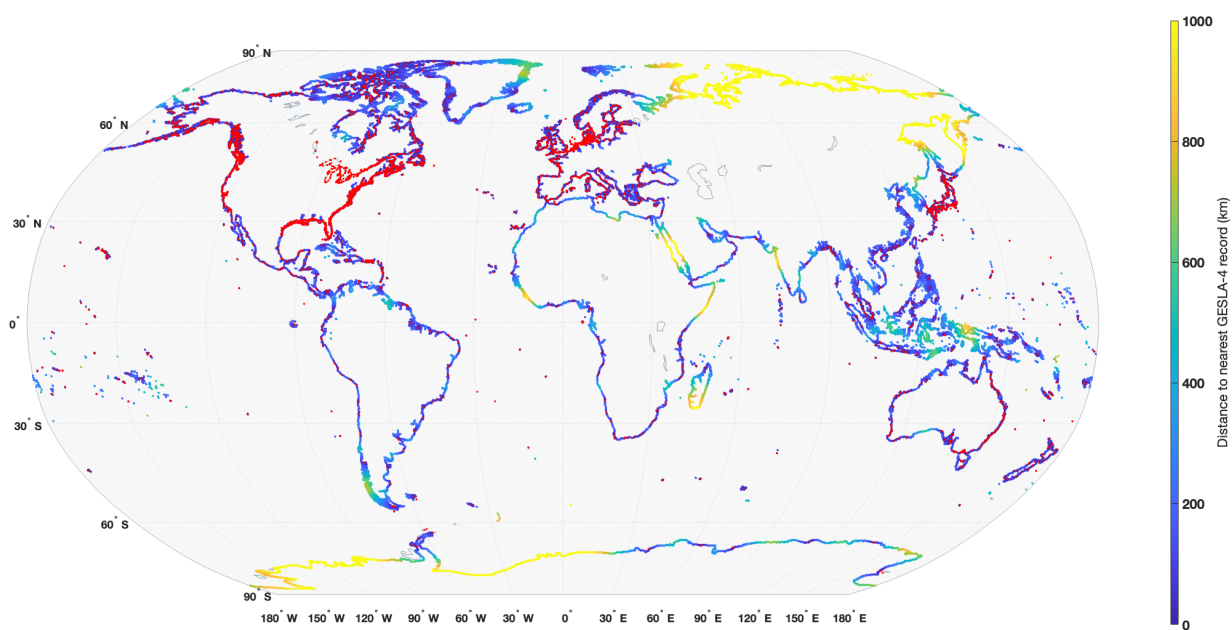


Figure 4: Distance (km) to nearest GESLA-4 record. Note, red dots indicate the tide gauge locations in GESLA-4.

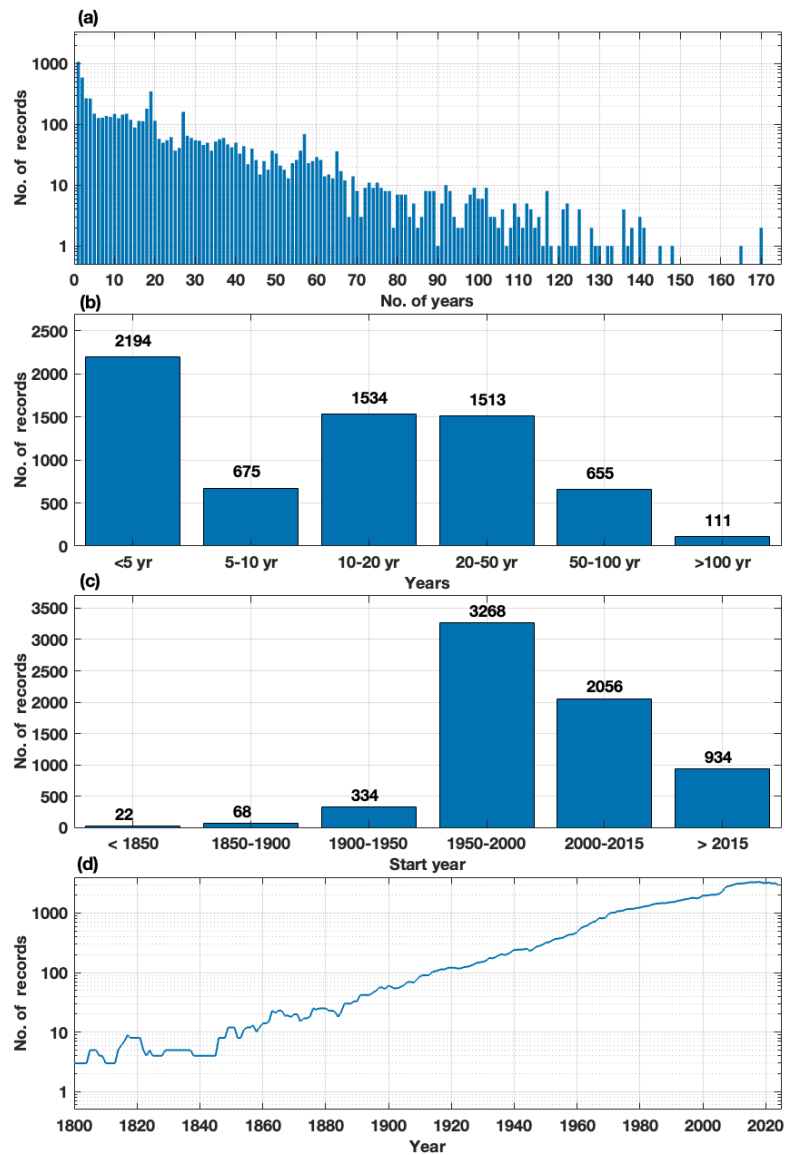


Figure 5: (a) Number of records with the stated number of years of data in GESLA-4 (note the logarithmic scale); (b) number of records with a particular number of years; (c) number of records with data starting in a particular span of years; and (d) number of records with data in a particular year (note the logarithmic scale).

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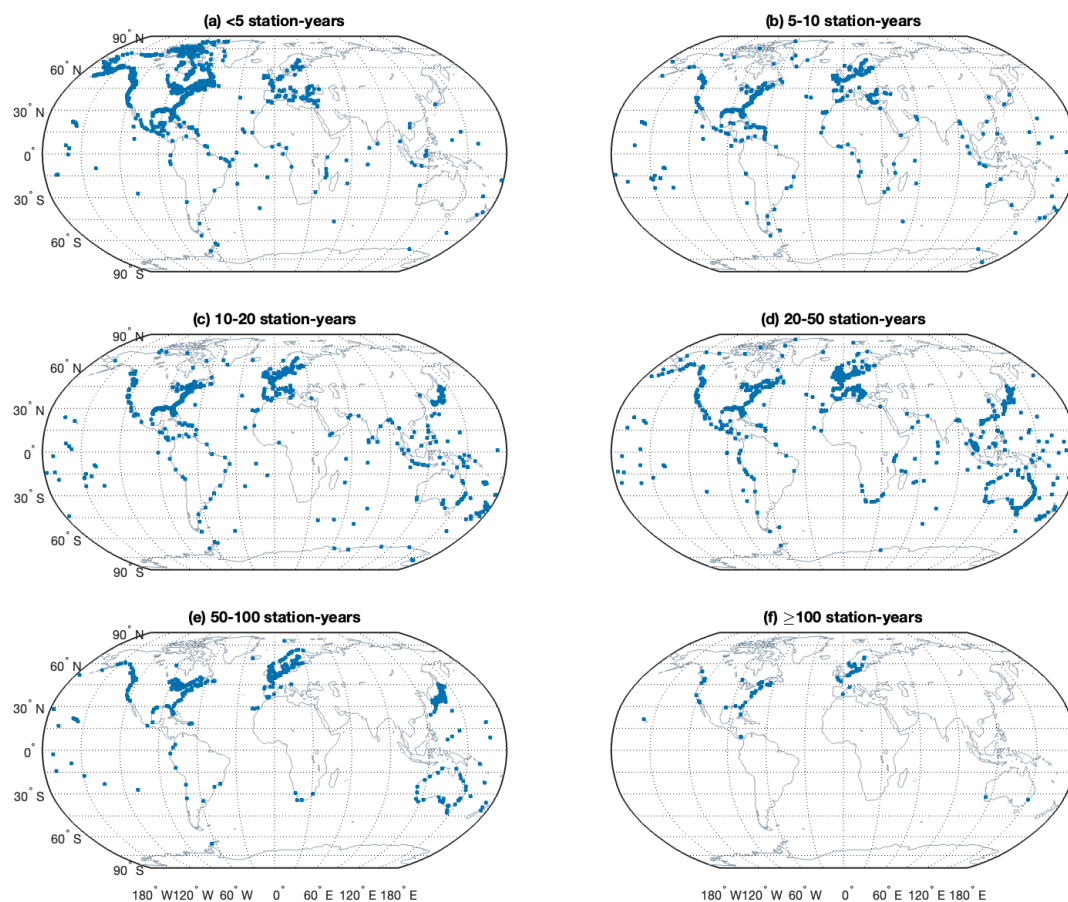


Figure 6: Locations of records in GESLA-4 with: (a) <5 station-years; (b) 5–10; (c) 10–20; (d) 20–50; (e) 50–100; and (f) >100.

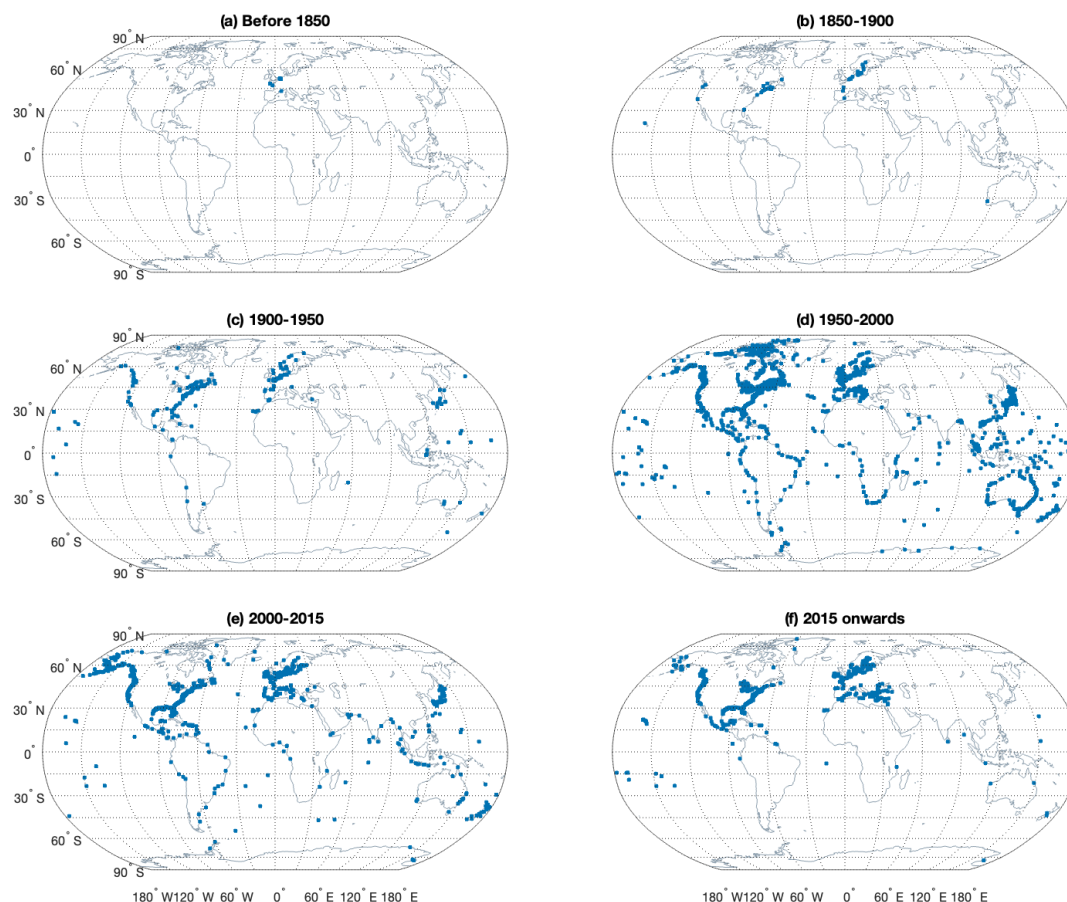


Figure 7: Locations of records with data starting in the years: (a) before 1850; (b) 1850–1900; (c) 1900–1950; (d) 1950–2000; (e) 2000–2015; and (f) after 2015.

2.2 Data processing and format

The processing and harmonisation procedures developed for GESLA-3 (Haigh et al., 2023) were retained for GESLA-4, with only the principal steps and changes summarised here.

Records obtained from the 43 contributing data sources were converted to a common format, with sea-level heights expressed in metres and timestamps referenced to Coordinated Universal Time (UTC). We were made aware, by users of GESLA-3, of potential time-zone inconsistencies in a small number of records, arising partly because some data providers do not explicitly specify the time zone associated with their observations. We therefore undertook a systematic review of the timing of all GESLA-4 records by comparing observed sea-level variability with coastal tidal predictions generated using the Oregon State University TPXO10-atlas (Egbert and Erofeeva, 2002). This process identified and corrected several



inconsistencies, including Daylight Saving Time adjustments that had not previously been applied to the RWS and CRMS datasets. Following these checks, we are confident that the vast majority of records in GESLA-4 are referenced to UTC. However, given the diversity of the original data sources, and the possibility that some agencies may have inconsistently applied time corrections in early records, we encourage users to contact us if they identify any remaining timing
 235 inconsistencies. Moreover, we note that tidal statistics in some gauges may show phase shifts due to timing errors (e.g., Zaron and Jay, 2014), river flow and depth variations, and long-term changes to the depth and geometry of estuaries (e.g., Beemster et al., 2026).

GESLA-4 continues to expand coverage in the upper reaches of estuaries and tidally influenced rivers, with many additional records added from these dynamic environments. As introduced in GESLA-3, records are classified according to
 240 their hydrographic environment as ‘coastal’, ‘river’, or ‘lake’. Coastal records are those where the tidal signal is clearly dominant, whereas river records show a substantial river influence on observed water levels and are often located farther upstream from the open coast. In many river records, daily tides only appear during low-river-discharge periods; however, the influence of tides on spring-neap and monthly time scales often intrudes much farther than daily variability (e.g., Hoitink and Jay, 2016). Lake records are from locations hydraulically disconnected from the ocean. Although our distinction between
 245 coastal and river environments is inevitably somewhat subjective, this classification provides users with a useful means of selecting records appropriate to their application. In GESLA-4, 5,332 records are classified as coastal, 1,160 as river, and 190 as lake, compared with 4,159, 784, and 178 records, respectively, in GESLA-3. The river sites are mostly located in the US and Europe. Lake records are predominantly located around the North American Great Lakes, with a smaller number in the IJsselmeer in the Netherlands.

Finally, provider-specific quality-control information was translated into the standard GESLA flagging system and supplemented by additional flags applied during our brief inspection of the records. Given the size of GESLA-4, it is not feasible for us to undertake comprehensive quality control of every record. Nevertheless, we visually inspect each record and, where only a limited number are present, flag obvious anomalous values or spikes. For CDWR data, datum shifts in the publicly available data at the California Data Library have been fixed using agency records, with some additional updates applied since
 255 GESLA-3 (see Lee et al., 2025, for additional information). The qualitative record-quality classification introduced in GESLA-3 has also been retained and updated for GESLA-4. Based on this visual inspection, each record is assigned to one of four categories: (a) no obvious issues; (b) possible datum issues; (c) possible quality-control issues; or (d) possible datum and quality-control issues. In GESLA-4, 5,823 records are classified as having no obvious issues, 174 as having possible datum issues, 581 as having possible quality-control issues, and 104 as having possible datum and quality-control issues, compared
 260 with 4,747, 149, 179, and 46 records, respectively, in GESLA-3. The increase in records with possible quality-control issues likely reflects, at least in part, the substantial expansion of GESLA to include records from a wider range of smaller regional and local monitoring networks, some of which were established primarily for operational rather than scientific purposes and may have less rigorous quality-control procedures. These classifications provide users with a broad indication of record quality and allow them to select records appropriate to their application; for example, analyses of long-term trends may benefit from



265 restricting the dataset to records with no obvious issues, whereas studies of individual events or shorter periods may make use
 of a broader selection of records. Importantly, a classification of ‘no obvious issues’ does not guarantee that a record is free
 from quality-control or datum problems. Given the size of GESLA, these classifications are based on relatively cursory
 screening, and more subtle issues may only become apparent through detailed examination of individual records.
 GESLA-4 retains the established GESLA-3 data-file structure, including date, time, observed sea level, the provider quality-
 270 control flag and a separate use-in-analysis flag. File naming also follows the convention established for GESLA-3, combining
 standardised site name, site code, country and contributor identifiers. Further details of these processing procedures and the
 rationale underlying the GESLA format are provided in Haigh et al. (2023).

2.3 Data licence

275 As for GESLA-3, the licensing conditions associated with each data source were carefully reviewed during the compilation of
 GESLA-4. Where explicit licence information was available, links to the applicable terms are provided in Table 1, together
 with an indication of whether the data may be used for both research and commercial purposes or for research purposes only.
 The conditions vary among providers, ranging from open licences requiring attribution to licences restricting commercial use.
 For a small number of sources, including City of Venice (CV), University of Zagreb (UZ) and CMEMS, use for commercial
 280 purposes requires additional permission from the original data owner; for records distributed through CMEMS, this may
 require contacting the organisation from which the data originated. GESLA-4 is distributed without user authentication and
 therefore does not enforce these conditions at the point of access. Responsibility for ensuring that individual records are used
 in accordance with their respective licence terms consequently rests with the user. We strongly encourage users to consult the
 information in Table 1 before using the data, particularly for commercial applications. Finally, the UHSLC dataset continues
 285 to make a major contribution to the spatial and temporal coverage of GESLA-4. In recognition of the considerable long-term
 effort involved in assembling, maintaining, and quality-controlling this dataset, users of GESLA-4 are requested to cite
 Caldwell et al. (2015), in addition to the present paper.

2.4 Data principles

290 As with GESLA-3, the development of GESLA-4 has been guided by the FAIR principles of making data findable, accessible,
 interoperable and reusable (Wilkinson et al., 2016), while ensuring appropriate recognition of the organisations responsible
 for measuring and providing the original observations. Many of the FAIR-related developments introduced with GESLA-3
 have therefore been retained, including persistent identification of the archived dataset through a Digital Object Identifier
 (DOI), indexing within searchable data resources, detailed record-level metadata, and clearer identification of data
 295 contributors, originators and licensing conditions. GESLA-4 makes further progress towards the FAIR principles through



substantially improved accessibility and machine-readable access. The new AWS-based services and UHSLC ERDDAP interface described in Section 5 enable selective and programmatic access to the database, while the provision of MATLAB and Python scripts through the GESLA website further supports reproducible data retrieval and analysis. Together, these developments reduce barriers to accessing and using GESLA and facilitate its integration into automated, reproducible and interoperable scientific workflows.

3 Evolution of GESLA

Since the first version of GESLA was assembled in 2009, the dataset has evolved substantially in its size, geographical coverage, record length, range of data sources, metadata, and accessibility. Each successive release has built upon its predecessor by incorporating newly available observations, extending existing time series, and responding to developments in how sea-level data are archived and distributed by regional, national, and international providers. Over the same period, GESLA has developed from a relatively small dataset assembled primarily for a specific research purpose into a widely used global community resource supporting research on tides, storm surges, extreme sea levels and a broad range of other coastal and oceanographic processes. Here we trace the evolution of the dataset, highlighting the major developments that have progressively expanded its coverage and improved its accessibility and usability (Section 3.1), and we briefly review the corresponding growth and diversification of the scientific publications and applications of GESLA (Section 3.2).

3.1 The evolving GESLA dataset

The origins of GESLA can be traced to a specific scientific need: to assemble quasi-global higher-frequency sea-level observations to investigate tides, storm surge, and extreme sea levels, and to understand the contribution of changes in mean sea level to variability in extremes. The first version of the dataset, GESLA-1, was assembled in 2009 by Philip Woodworth, John Hunter and Melisa Menéndez and contained 20,501 station-years of observations across 675 records. Much of the dataset was assembled from the UHSLC and other sources contributing to GLOSS, supplemented by records obtained from national data centres and directly from colleagues within the sea-level community. Assembling such a dataset was considerably more difficult at that time than it is today. Relatively few national sea-level data providers maintained online data portals, and the conditions governing redistribution of observations were often unclear. Consequently, although permission had generally been obtained to use the individual datasets, a sufficiently detailed record of redistribution permissions had not been maintained during the compilation of GESLA-1. The complete database therefore could not be made openly available and was instead shared directly with trusted scientific collaborators. This experience highlighted an important requirement for subsequent versions of GESLA: alongside increasing the quantity and geographical coverage of the observations, the provenance and conditions governing redistribution of the source data needed to be documented much more systematically.



The second generation, GESLA-2, was assembled during 2015–2016 by Philip Woodworth, John Hunter, Melisa Menéndez, Marta Marcos and Ivan Haigh and is described in Woodworth et al. (2016). By this stage, the archive had almost doubled in size, reaching 37,926 station-years across 1,353 records assembled from 30 data providers. An important development was the more explicit consideration of data-access and redistribution conditions associated with the contributing
 330 sources. The archive was divided into 27 “public” and three “private” subsets. Subject to acknowledgement of the data owner, the public data were freely downloadable from the dedicated GESLA website and could be used for both research and commercial purposes. The private subsets were restricted to research use and were password protected, with bona fide researchers required to contact the GESLA team and explain their intended use before being granted access. Thus, GESLA-2 represented more than a substantial expansion of GESLA-1: it marked the transition from a research dataset circulated
 335 primarily among collaborators to a largely open and accessible resource for the wider scientific community.

The third generation, GESLA-3, was compiled during 2020–2021 by a team led by Ivan Haigh, Marta Marcos, Stefan Talke, Philip Woodworth, John Hunter, Ben Hague, Arne Arns, Elizabeth Bradshaw, and Philip Thompson, and represented a much larger expansion of the database, and is described in Haigh et al. (2023). It contained 91,021 station-years across 5,119 records obtained from 36 data sources, more than doubling the total observational coverage of GESLA-2 and almost
 340 quadrupling the number of individual records. Geographical coverage was also substantially improved, with observations available from 114 countries and particularly large additions in regions such as Japan, Australia, North America and Europe. Importantly, this expansion included not only additional long records but also many shorter records from regional and national monitoring networks, including gauges in the upper reaches of estuaries and tidally influenced rivers, broadening the spatial density of observations available for applications where geographical coverage is as important as record length. GESLA-3 also
 345 incorporated sea-level data obtained from paper records via data archaeology exercises. GESLA-3 placed greater emphasis on consistent processing, metadata, quality-control information, data provenance, licensing and the FAIR principles, further developing GESLA from a compiled collection of observations into a more systematically documented global data resource.

The fourth generation, GESLA-4, compiled during 2025–2026 by the authors of this paper, continues this progression. The current GESLA-4.1 release contains 136,069 station-years across 6,682 records obtained from 43 data sources and
 350 spanning 119 countries, representing increases of 45,048 station-years and 1,563 records relative to GESLA-3. In addition to incorporating new sources and extending many existing records, GESLA-4 has provided an opportunity to revisit the consistency of the archive, including a systematic review of record time zones. The increasing availability of observations through APIs and other machine-readable services is also allowing parts of the acquisition and updating process to become increasingly automated, although considerable manual effort remains necessary because of differences among providers in
 355 formats, metadata, quality-control procedures and data-access arrangements. Perhaps the clearest illustration of the evolution of GESLA is the way in which users access the observations. GESLA-1 was shared directly with individual researchers; GESLA-2 established public distribution of the majority of the database through the GESLA website (with a small private subset for which there were restrictions); GESLA-3 strengthened metadata, provenance, and FAIR data practices and the whole dataset was made available; and GESLA-4 now adds programmatic access through AWS and an ERDDAP server hosted by



360 UHSLC. Users can now query individual stations, time periods, and variables and retrieve only the observations required for a particular application, facilitating automated and reproducible scientific workflows.

As summarised in Table 3, the number of records has increased 10-fold from 675 in GESLA-1 to 6,682 in GESLA-4.1, total coverage has grown nearly 7-fold, from 20,501 to 136,069 station-years, and the number of contributing data sources has tripled from 13 to 43. GESLA-1 and GESLA-2 emphasised longer records suitable for investigating long-term variability and change, including changes in storm-surge climatology. In contrast, GESLA-3 and GESLA-4 incorporated substantially shorter records, and records in estuaries and tidal rivers, to support a widening range of applications: records shorter than five years increased from 45 and 191, in GESLA-1 and GESLA-2, to 1,993 and 2,194, in GESLA-3 and GESLA-4, respectively. This broader inclusion was accompanied by stronger historical coverage, with the number of records longer than 100 years increasing from 17 in GESLA-1 to 111 in GESLA-4.1 and the earliest observations extending back from 1846 to 1800. This expansion represents both data rescue efforts and the passage of 17 years since the first data compilation. Beyond these quantitative gains, successive versions have improved geographical coverage, documentation, consistency, accessibility and reproducibility. The underlying philosophy has nevertheless remained consistent: to bring together higher-frequency sea-level observations maintained by diverse organisations, preserve their provenance and ensure appropriate recognition of their providers, and facilitate their discovery and use by the wider scientific community.

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Table 3: Comparison of GESLA versions 1, 2, 3, and 4, showing the numbers of data sources, records, and record-years; the distribution of records by length and start year; and the earliest and latest years represented.

Metric	GESLA-1	GESLA-2	GESLA-3	GESLA-4
Overall coverage				
Number of sources	13	30	36	43
Number of records	675	1,353	5,119	6,682
Total record-years	20,501	37,926	91,021	136,069
Record length (years)				
<5	45	191	1,993	2,194
5–10	49	187	672	675
10–20	184	217	927	1,534
20–50	296	527	969	1,513
50–100	84	208	489	655
>100	17	23	69	111
Record start year				
<1850	2	2	10	22
1850–1900	11	13	54	68
1900–1950	111	133	269	334
1950–2000	544	1,059	2,810	3,268
2000–2015	7	146	1,470	2,056
>2015	0	0	506	934
Temporal extent				
Earliest year	1846	1846	1800	1800
Latest year	2008	2015	2021	2026



3.2 The scientific use and applications of GESLA

380 The scientific use of GESLA has grown substantially in both volume and breadth since the dataset was first assembled. We reviewed 275 peer-reviewed journal articles citing the GESLA-2 paper (Woodworth et al., 2016), the GESLA-3 paper (Haigh et al., 2023), or both, and identified 205 papers that directly used GESLA observations for analysis, model development, validation or comparison. The remaining 70 papers cited GESLA without directly using the data. Through this review, we identified 15 broad categories of GESLA use by grouping studies with similar scientific objectives and applications of the observations. We defined these categories according to the principal research purpose for which GESLA was used and assigned each data-using study to a single primary category. Although this simplifies studies spanning several topics, it provides a consistent overview of scientific uptake and diversification. Theses, unpublished reports and grey literature are excluded from these publication counts; GESLA's contribution to Intergovernmental Panel on Climate Change (IPCC) assessments is considered separately below.

390 Annual publication numbers have increased substantially across successive generations of GESLA, as illustrated in Figure 8a. Only seven identified studies used GESLA-1 during 2010–2016, including analyses of extreme sea levels (Menéndez and Woodworth, 2010), tides (Woodworth, 2010), and sea-level-rise allowances (Hunter, 2012). Following the public availability of GESLA-2, the annual number of studies increased from six in 2017 to 16 in 2020. Uptake accelerated further as GESLA-3 became available, with 24 studies identified in 2023, 31 in 2024 and 45 in 2025. A further 28 were identified up to September 2026, including five using GESLA-4. Because 2026 represents only a partial publication year, this total should not be interpreted as a decline in use.

The 205 data-using publications span 15 primary application categories, listed in Figure 8b, reflecting the breadth of GESLA's scientific use. Storm-surge climatology and tidal analysis and harmonic change are the largest application categories, each accounting for 34 publications, followed by extreme-value analysis (29) and hydrodynamic modelling (23). Together, these four categories comprise 120 of the 205 studies (59%). They encompass investigations of sea-level variability, seasonality and trends, estimation of return levels, and evaluation of numerical simulations. Examples include analyses of storm-surge seasonality (Barroso et al., 2025), changing coastal storm extremes (Morim et al., 2025), and global storm-surge projections (Muis et al., 2023). GESLA also underpins derived observational products, notably the TICON tidal-constituent datasets (Piccioni et al., 2019; Hart-Davis et al., 2025).

405 The remaining applications demonstrate the broader value of geographically distributed higher-frequency observations. Compound flooding accounts for 15 studies, combining coastal sea levels with river discharge, precipitation or other hazard components (e.g., Ward et al., 2018; Ganguli and Merz, 2019). Fourteen studies focus on flood exposure, impacts and risk, linking observed extremes to societal consequences and adaptation needs (e.g., Kirezci et al., 2020; Hermans et al., 2023). Data-driven and machine-learning methods account for 11 studies, using GESLA for training and evaluation of sea-level and storm-surge reconstructions and predictions (e.g., Tadesse et al., 2020; Tiggeoven et al., 2021). Further applications



include remote sensing and altimetry (10), dataset and software descriptors (9), tide–surge interaction (9), sea-level reconstruction (7), coastal geomorphology and ecosystems (3), vertical land motion and datums (3), tide-gauge data quality (2), and other applications (2).

Figure 8b illustrates how these applications have emerged and grown through time, with ribbon thickness representing the cumulative number of publications in each application area. Early applications were concentrated primarily on storm-surge climatology, extreme-value analysis and tides, but the range of uses broadened markedly from around 2018 onwards. More recent applications include compound flooding, machine learning, remote sensing, hydrodynamic modelling and coastal impacts. This diversification demonstrates how GESLA has evolved from a dataset used predominantly for storm-surge climatology, extreme sea-level analysis and tidal studies into a broader observational resource for coastal science, including as a benchmark for evaluating numerical models, satellite products and data-driven methods.

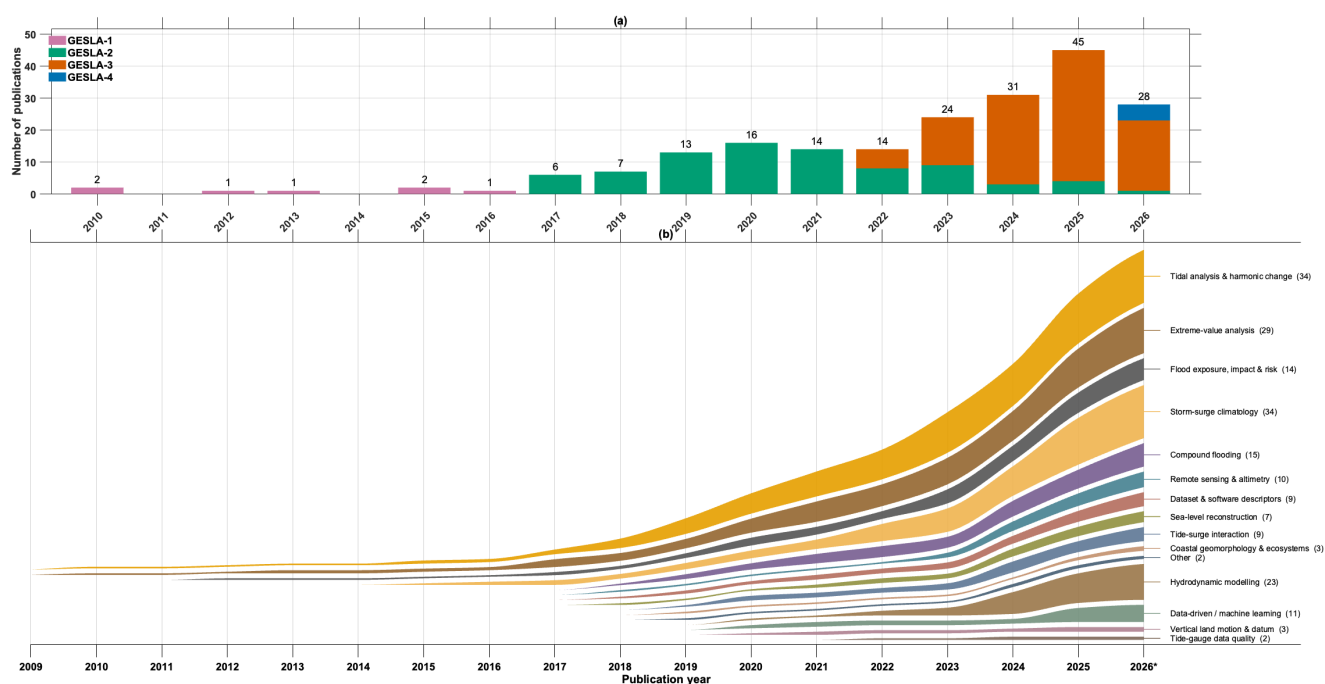


Figure 8: (a) Annual number of publications using each of the four generations of GESLA; and (b) growth and diversification of GESLA applications through time, with ribbon thickness representing the cumulative number of publications in each application area. Numbers in parentheses in (b) indicate the total number of publications in each application area. The 2026 literature search covers a partial publication year (to September 2026); 70 citation-only articles are excluded.

GESLA has also contributed to IPCC assessments of sea-level change. Analyses using GESLA-1 were assessed in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; IPCC, 2012) and three chapters of the Fifth Assessment Report: Working Group I Chapters 3 and 13 and Working Group II Chapter 5 (Rhein et al., 2013; Church et al., 2013; Wong et al., 2014). These analyses provided evidence that widespread



increases in extreme sea levels were largely associated with rising mean sea level. GESLA-2 was subsequently used directly in the Special Report on the Ocean and Cryosphere in a Changing Climate and the Sixth Assessment Report to assess how sea-level rise alters the frequency of extreme coastal water levels (Oppenheimer et al., 2019; Fox-Kemper et al., 2021). Together, these applications demonstrate GESLA's role as an observational foundation for assessing past and future changes in coastal flood hazard.

4 Discussion

This paper has described the development and release of GESLA-4, the fourth generation of the Global Extreme Sea Level Analysis dataset. GESLA-4 represents a substantial expansion since GESLA-3, with an additional 45,048 years of observations and 1,563 records. Many existing records have also been extended through July 2026, typically providing a further three to four years of observations, compared to GESLA-3. GESLA-4 is not simply an extension of GESLA-3: the compilation has also provided an opportunity to revisit aspects of the processing and consistency of the archive, including a comprehensive review of record time zones.

Maintaining a global dataset assembled from many regional, national, and international providers remains a substantial undertaking. GESLA continues to be compiled without dedicated funding, with the work undertaken by the team as a contribution to the wider scientific community. The process is becoming more efficient as a growing number of providers make observations available through APIs and other machine-readable services, allowing data acquisition and updating to be increasingly automated. Nevertheless, substantial manual effort is still required because providers use different data structures, metadata conventions, and quality-control flags. Substantial local knowledge and sleuthing are often required to find and obtain records from regional databases and providers, particularly when there are language barriers. Data-access arrangements can also change between GESLA releases: websites may be reorganised or become unavailable, APIs and file structures can change, and historical records may be revised by their original providers. Maintaining GESLA is therefore an ongoing process rather than a simple periodic extension of existing time series. More records are known to exist but are not yet incorporated into the dataset. In the future, artificial intelligence may facilitate record concatenation and normalisation, which up to now has been labour-intensive and a barrier to further development.

A particularly important development in GESLA-4 concerns how users can access the database. GESLA-1 was distributed on request, while GESLA-2 and GESLA-3 made the complete database directly downloadable through the GESLA website. GESLA-4 takes the next step by also providing access through an ERDDAP server hosted by the UHSLC and direct download links (facilitated by AWS) for individual station records embedded in the supplied CSV and KML files. This responds to a frequent request from users and allows individual sites and specified time periods to be queried and downloaded without retrieving the complete archive. Programmatic access also makes GESLA substantially easier to incorporate into reproducible analyses, automated processing pipelines and applications requiring repeated or regularly updated data retrieval.



Important challenges nevertheless remain. The level of quality control applied to the original observations varies considerably among data providers, and some records within GESLA-4 contain observations that have undergone limited or no quality control. Applying a consistent, comprehensive quality-control procedure to more than 136,000 station-years of observations has not been possible with the resources currently available to the project. Existing developments in automated tide-gauge processing, including statistical screening and machine-learning approaches, provide a foundation for addressing this challenge (Williams et al., 2019; Lin-Ye et al., 2023; Bauer et al., 2026). Adapting and validating such methods across GESLA's diverse records is therefore an important priority for future releases, with particular attention to distinguishing instrumental errors from genuine extreme events. These approaches should complement the specialist quality control and knowledge of station histories provided by the organisations responsible for collecting and maintaining the original observations.

A further challenge is the presence of overlapping and, in some cases, duplicate records obtained through different data providers. For example, observations for Newlyn are available through UHSLC, BODC, and CMEMS, while Brest is represented through UHSLC, REFMAR, and CMEMS. Retaining these records in the main GESLA archive maximises the information available from the different sources but places some responsibility on users to identify overlapping records when undertaking regional or global analyses. We have recently made substantial progress in identifying these overlaps and developing a duplicate-free subset of GESLA, in which a single preferred record is selected where multiple records represent the same tide-gauge location. We plan to make this subset available later in 2026, providing users with a simpler option for applications requiring a unique set of stations, while continuing to retain the complete collection of source records within the main GESLA archive.

A further challenge concerns the vertical datums to which sea-level observations are referenced. Datum descriptions supplied with tide-gauge records do not always establish a relationship to a national or geodetic reference system; labels such as "tide gauge zero" are insufficient on their own to determine this relationship. Without a documented connection to a common vertical reference, users cannot reliably compare absolute sea levels between sites or infer changes in mean sea level between non-overlapping records at the same location. Recovering these connections requires benchmark information, levelling records and knowledge of historical changes in gauge reference levels, which can be difficult or impossible to obtain for older observations. Improved datum documentation therefore remains an important priority. We encourage data providers and researchers to contribute recovered datum histories and verified connections to external reference systems, together with their uncertainties, to strengthen the value of GESLA for applications requiring consistent vertical referencing.

We strongly encourage users to contact us if they identify any errors, inconsistencies, or other issues within GESLA-4, and to inform us of higher-frequency sea-level datasets or individual records that are not currently included. Although the GESLA team has limited time and resources available for maintaining the database, we will endeavour to investigate reported issues and address them in future updates wherever possible. Contributions from data providers and feedback from the wider user community remain essential to improving the quality, coverage, and usability of GESLA.



495 Alongside the continued development of GESLA, a companion dataset, GLOBES (Global Library of Observations
from Buoys for Evaluating Sea States), is being developed. Building on the philosophy and experience of GESLA, GLOBES
aims to assemble and standardise in situ wave observations from as many moored buoy sites around the world as possible,
bringing together records currently distributed across numerous national, regional and international data providers. The dataset
is intended to provide a readily accessible global resource for investigating wave conditions and extremes, their spatial and
500 temporal variability, and their relationships with other coastal and oceanographic processes, as well as for coastal hazard
assessment and engineering applications. Development of GLOBES is currently underway (Quadrado et al., in prep.), and we
anticipate releasing the first version later in 2026. Together, GESLA and GLOBES will provide complementary global
observational resources for investigating extreme sea levels and waves and the processes that generate coastal hazards.

 Despite advances in physics-based modelling, statistical methods, machine learning and satellite remote sensing, in
505 situ sea-level measurements remain indispensable for developing and evaluating these approaches. Tide-gauge observations
provide a direct observational reference for model calibration and validation, enabling researchers to assess how well different
methods reproduce the magnitude, timing and variability of coastal sea levels, particularly during extreme events. The value
of a spatially extensive repository such as GESLA therefore extends beyond analyses of the observations themselves: it
supports consistent evaluation across diverse tidal regimes, coastal settings and climatic conditions, helping to identify
510 systematic biases and establish where methods can be applied reliably. Although their use requires careful consideration of
record quality, representativeness and spatial coverage, these observations provide the empirical foundation on which
increasingly sophisticated approaches depend. Sustaining and expanding sea-level monitoring networks, recovering and
digitising historical observations, and preserving, standardising and sharing the resulting data remain essential to improving
coastal sea-level predictions and hazard assessments.

515 Data archaeology offers substantial opportunities to extend GESLA further back in time. Many historical sea-level
observations remain in handwritten or printed ledgers and paper marigrams, awaiting conversion into usable digital time series
(Latapy et al., 2023; Talke and Jay, 2013). A recent inventory identified 631 undigitised records representing approximately
7,441 years of observations across the studies reviewed, demonstrating the scale of this untapped resource (Kenwright et al.,
2026a). Recovering suitable higher-frequency records could extend existing series, fill historical gaps and improve
520 understanding of long-term changes in tides and extreme sea levels. However, digitisation remains labour-intensive: an
evaluation of tools applied to a historical marigram found that conventional approaches required substantial human input,
while the two large language models tested were insufficiently accurate under the conditions examined (Kenwright et al.,
2026b). Progress therefore requires sustained support for locating, preserving, scanning and digitising historical records,
alongside the recovery of associated timing and datum information and careful quality control. We encourage researchers and
525 archive holders to help identify and recover these observations for inclusion in future GESLA releases.



5 Data Availability

All 6,682 records in GESLA-4 can be downloaded together as a single zip file directly from the GESLA website (<https://www.gesla.org>), where earlier versions of the dataset are also available. As with GESLA-3, we provide a comma-delimited ASCII (CSV) file containing metadata for each record and a Keyhole Markup Language (KML) file that can be opened in applications such as Google Earth to visualise station locations and associated information. Previous releases required users to download the complete dataset even when only a small number or regional subset of records was needed, creating practical barriers for users with limited bandwidth or storage and making the data less suited to programmatic workflows increasingly used in data science, machine learning and reproducible research. GESLA-4 addresses these limitations by providing direct, on-demand access to individual station records. Direct download links are included in the CSV and KML files, with individual station files stored in Amazon S3 and delivered through Amazon CloudFront. A cloud-based REST API also allows users to query station metadata and access individual records programmatically from environments such as Python, MATLAB and R, supporting efficient selective access and automated workflows.

Another major improvement in data accessibility is the availability of GESLA-4 through an ERDDAP server hosted by the UHSLC (https://uhslc.soest.hawaii.edu/erddap/tabledap/global_hourly_gesla.html). Whereas the GESLA REST API described above provides direct access to individual station records in their original GESLA format, ERDDAP provides greater flexibility for querying and subsetting the database. Users can select individual or multiple tide-gauge sites, specify time periods, and filter observations using available metadata fields, retrieving only the data required for a particular application. Selected data can be downloaded in a wide range of commonly used formats, including CSV, JSON, NetCDF, MATLAB and plain text, facilitating direct use across different software environments and analysis workflows. ERDDAP also supports scripted access, providing an alternative interface for incorporating GESLA into automated and reproducible workflows. Together, the GESLA direct-download and REST API services and the UHSLC ERDDAP interface provide complementary approaches for accessing the database, ranging from individual records in their original GESLA format to customised subsets in a range of analysis-ready formats.

The dataset is also archived with Zenodo with the Digital Object Identifier (DOI) <https://doi.org/10.5281/zenodo.22712060> (Haigh, 2026).

6 Code Availability

MATLAB and Python scripts to read GESLA formatted files are made available on the GESLA website (<https://www.gesla.org>).



7 Conclusions

555 With more than 136,000 years of observations from 6,682 records, GESLA-4 provides an extensive observational resource for investigating tides, storm surges, extreme sea levels, and other processes operating from hourly to multi-decadal timescales. Its increased spatial and temporal coverage, together with improved processing and substantially enhanced data accessibility, should enable an even wider range of scientific and applied uses. We hope that GESLA-4 will support new understanding of the processes controlling coastal sea levels and extremes, their variability and long-term change, and ultimately contribute to improved assessment of the risks faced by coastal communities in a changing climate.

Author contributions

IDH led the study, including conceptualization, methodology, project administration and supervision, and wrote the original draft of the manuscript. MM, SAT, BSH, JGWB, CK and AM contributed to data acquisition, curation and processing. SW and PT developed and implemented the UHSLC ERDDAP data-access system. MN developed and implemented the AWS-
565 based data-access system. MGHD, TW and GPQ contributed to methodological development. IDH and JECB conducted the literature review and classification of studies citing previous versions of GESLA. All authors contributed to reviewing and editing the manuscript and approved the final version. During the preparation of this manuscript, the authors used generative AI tools to assist with proofreading, drafting and refining text, and identifying the primary application areas of the 205 published studies that analysed GESLA observations. The authors reviewed and verified the suggested classifications, critically
570 reviewed and edited all AI-assisted text, and take full responsibility for the final content and accuracy of the publication.

Competing interests

The authors declare no conflicts of interest.

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