The Swedish Sea Level network

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Introduction

The Swedish Sea Level network, operated by the Swedish Maritime Administration (SMA), Swedish Meteorological and Hydrological Institute (SMHI), Swedish Nuclear Fuel and Waste Management Company (SKB), Chalmers (CTH), Port of Gothenburg (GBG) and University of Gothenburg (GU) records sea level at 60 locations (Figure 1 and Appendix 1). The Swedish sea level records constitute some of the longest and most robust sea level records in the world (Table 1, Appendix 1).

Figure 1. The Swedish Sea Level network in January 2025.

The Swedish Sea Level network

The first systematic Swedish observations of the sea level started 1774 at the sluice in the harbour of Stockholm. New stations were established in the 1840s to investigate the mechanism behind what was during that time called the “water sinking effect”, nowadays referred to as the land-uplift, due to the isostatic adjustment since the last glacial period. The first results of the observation activities ended up in a wider acceptance that it is the land that rises from the sea.

At the end of 19th century, the Swedish king, Oscar the second, decided to establish seven mareographs, primarily to investigate the land uplift effect. Several of these mareographs are still in operation or have been substituted by other stations. In 1889 the Nautical-Meteorological Bureau, a predecessor of SMHI, established a continuously recording sea level station (mareograph) in the bedrock on the island Skeppsholmen (Figure 2), located close to the sluice. This mareograph has since then recorded the Stockholm sea level. The sea level series in Stockholm constitutes the longest sea level record in the world (Figure 3).

Figure 2. The Swedish GLOSS-station (mareograph), located on the island Skeppsholmen in Stockholm.

During the 20th century several more stations were established. The technique used from the beginning was the stilling well technique. The Sea Level network was completely modernised during the 1980s. The traditional stilling well was still used, but the gauges were converted from analogue to digital with automatic data transfer to SMHI. Earlier the recording was only done with a chart recording apparatus. In the beginning of 21th century (2001-2005), a new upgrade of the stations was completed and shaft encoder were installed at almost all stations. The chart apparatus was kept as a backup for the digital recording equipment, mainly to prevent gaps in the time-series. Later, this equipment has been replaced by radar- and pressure sensors (see Upgrade of the Swedish Sea Level network below).

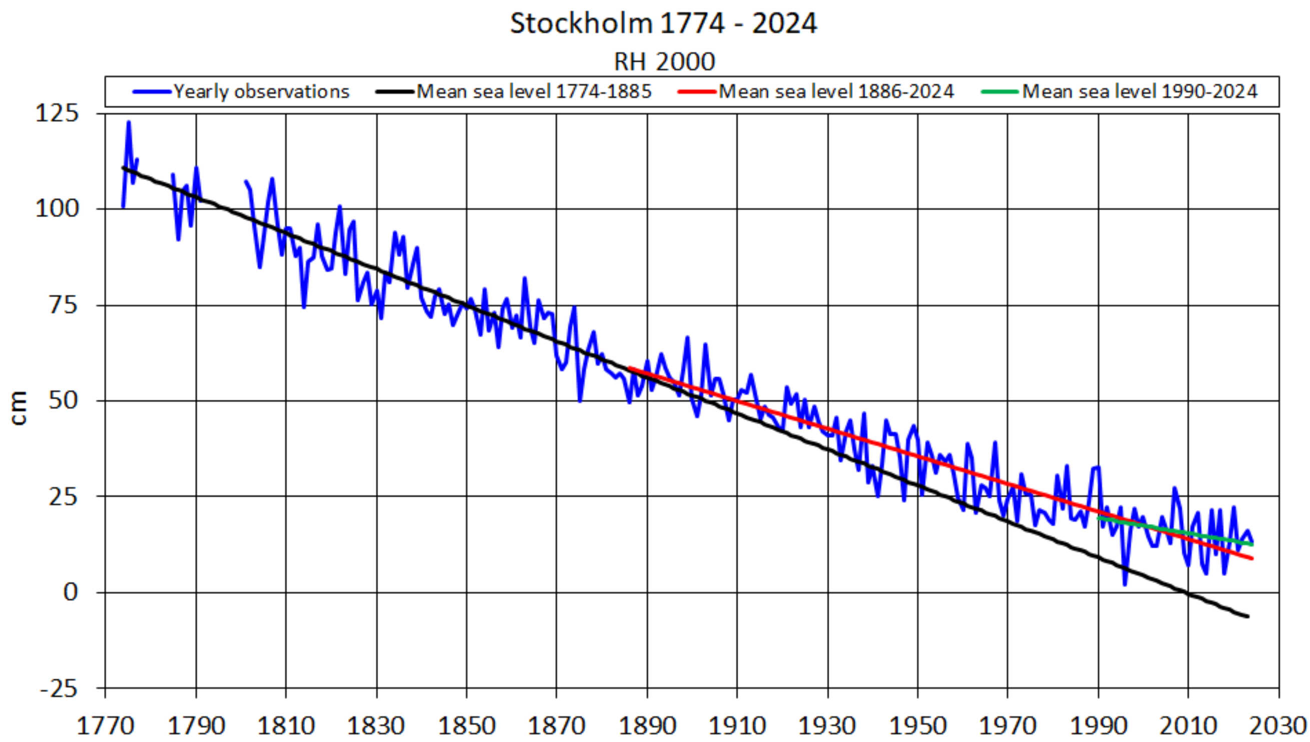

Figure 3. Annual mean sea levels in Stockholm since 1774, with the black, red and purple regression lines corresponding to the land uplift 1774-1885 (0.47 cm/year), 1886-2024 (0.38 cm/year) and 1990-2024 (0.21 cm/year), respectively. The increased sea level rise since the late 19th century appears as the deviation from the black regression line (extended into modern times).

Climate changes in sea level data

From the long Swedish time series of sea level, we can detect the global sea level rise after reducing the yearly means with the land-uplift effect (Figure 4). A regression analysis indicates a sea level rise around 3 mm per year for the last 40 years and approximately 1.6 mm per year since 1886. Where the land-uplift is small, as around the coasts of southern Sweden, the sea level has risen approximately 20 centimetres since 1886.

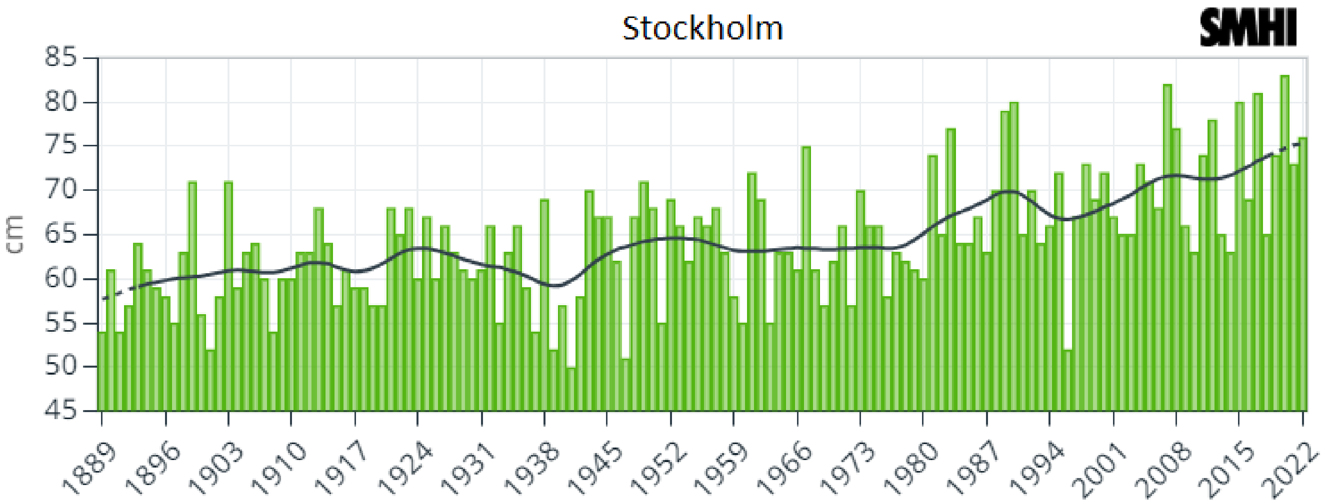

Figure 4. Observed sea level change in Stockholm since 1889. Sea level corrected for the land-uplift (glacial isostatic adjustment). The black line shows the gauss-filtered (smoothed) average.

Upgrade of the Swedish Sea Level network (SHIP)

For several years, SMA and SMHI have had a close cooperation on oceanographic observations. In the EU-financed FAMOS Odin-project (2017-2019), SMA and SMHI have decided to establish a joint Swedish Sea Level network (Figure 1). The project to upgrade the network was called SHIP. The existing stations have been upgraded with new sensors and the communication to the stations have been improved. New sensors and data loggers was installed that is more capable of delivering near real time data. The data recorded by the measurement equipment is transferred to SMA every minute and stored in a database. From there, the data can be presented in real-time on websites and be distributed further to the users. SMHI is responsible for the delayed mode quality control and long-term storage of the data. A software application connected to the database is used for validation and correction of the data. Data are distributed to users via national and international data exchange (Table 2) on a continuous basis.

A classification is done for the stations in the new network. The stations are now divided into four different classes, based upon user needs. Class 1-stations consist of stations with duplicated sensors (two radar sensors or one radar and one pressure sensor), a logger installed at the stations and a battery backup making it possible to re-collect data missing in real-time. Class 2-stations will also have duplicated sensors (one radar and one pressure sensor), including a logger but without battery backup and hence without the possibility to recover data missing in real-time. Class 3-stations will be unchanged and Class 4-stations will be dismantled. Dismantled stations are mostly located at places where both SMA and SMHI measures today. The stations will be moved or be replaced by one upgraded station only.

The mareograph´s at SMHI with long time series, starting in the late 19th century have been classified as Class 1-stations and the long time series will be continued. At the Class 1-stations, an observer will visit the station every two weeks and check the status of the station and validate real-time data. There is 54 upgraded Class 1- and 2- stations in the new Swedish Sea Level network and six Class 3-stations. Summarized, in October 2022, the Swedish Sea Level network consists of 60 stations. In addition, several sea level stations, established by private partners and local harbour offices, will be included in the network in a near future. For example, three stations owned and operated by the Gothenburg harbour have already been included in the network in 2018, which have been classified as Class 2 stations.

Each sea level station is connected to several Bench Marks. The Swedish mapping, cadastral and land registration authority (Lantmäteriet) does the precise levelling, i.e. they are responsible for determining the distance between the Contact Point and the Bench Marks. SMA and SMHI shared the responsibility for the maintenance and ‘local’ levelling of the stations. The Tide Gauge Zero (TGZ) will be kept at a fixed distance below the Contact Point. Most of the gauges are installed in the bedrock, but some are located in slightly unstable areas. Levelling is done every three years. The levelling often shows no significant vertical motion on the majority of the sea level stations.

Co-location of geodetic observing system at mareographs

The Swedish mapping, cadastral and land registration authority (Lantmäteriet) has developed the geodetic infrastructure at several of the mareographs (Figure 5, Table 1) to include connection to the national height levelling network, continuous GNSS as well as absolute gravimetric measurements. GNSS at mareographs was first done as a GPS-campaign during the European project EUVN in 1997. The monuments have later been equipped with Continuous Global Positioning (CGPS), and are now part of the Swedish CORE network named SWEPOS™.

The main purpose of these techniques has been to develop a model to describe the post glacial rebound. One of the main tasks for the geodetic research division at Lantmäteriet is to develop, monitor and maintain the national reference systems and frames in all dimensions (3D, horizontal, height) as well as gravity so that the need of the society is satisfied. The national levelling network was levelled during the third precise levelling of Sweden during 1978-2001 and resulted in the national height system RH 2000, which is the Swedish realization of the European Vertical Reference System (EVRS), which is referred to Normaal Amsterdams Peil (NAP).

Lately, several different Nordic institutions as well as other international actors have observed gravity with absolute gravimeters in the Nordic and Baltic area. These efforts have been co-ordinated through the working group of geodynamic within NKG (Nordic Commission of Geodesy). The main purpose of these measurements has been to detect the change of gravity over time, mainly caused by the post glacial rebound. Several mareographs are today equipped with an absolute gravity platform (Figure 5). Levelling is performed continuously (Figure 6).

Figure 5. Smögen, a mareograph (hut to the left) also combined with CGPS (monument to the right) and absolute gravity platform (hut in the middle).

Station	Latitude	Longitude	Digital data available from	Installation and type of CGPS	Distance to CGPS (km)	Install ation of AG
KALIX STORÖN	65.697056	23.096014	1974	-	-	-
FURUÖGRUND	64.915639	21.230675	1916	1993A	9.5	1992
RATAN	63.986042	20.894989	1891	2006A	0.058	2007
SKAGSUDDE2 (Skagsudde)	63.190519	19.012345	2018 (1982)	-	-	-
SPIKARNA (Draghällan)	62.363333	17.531111	1968 (1897)	-	-	-
FORSMARK (Björn)	60.408500	18.210850	1975 (1891)	-	-	-
STOCKHOLM (Nedre Stockholm)	59.324200	18.081700	1889 (1774)	1992A/2013B	15.2/0.373	-
LANDSORT NORRA (Landsort)	58.768653	17.858872	2004 (1886)	-	-	-
ARKÖ (Marviken)	58.483147	16.963647	2014 (1964)	2019B	0.158	-
VISBY	57.639242	18.284503	1916	1993A	5.2	2004
ÖLANDS NORRA UDDE	57.366278	17.097228	1851	2004B	13.5	-
OSKARSHAMN	57.271569	16.479922	1960	-	-	-
KUNGSHOLMSFORT	56.105194	15.589278	1886	2004A	0.108	-
SIMRISHAMN (Ystad)	55.557611	14.357722	1982 (1886)	-	-	-
YSTAD2 (Ystad)	55.422742	13.825672	2014 (1886)	2011B	2.170	-
SKANÖR (Ystad)	55.416789	12.829633	1992 (1886)	2002B	1.8	-
KLAGSHAMN (Malmö)	55.522300	12.893628	1929 (1924)	-	-	-
BARSEBÄCK	55.756400	12.903410	1937	2002B	5.9	-
VIKEN	56.142142	12.579267	1976	-	-	-
RINGHALS (Varberg)	57.249756	12.112531	1967 (1886)	1991A	19.7	1993
ONSALA (Varberg-Ringhals)	57.391944	11.918889	2015 (1886)	1993A/2012B	0.533/0.496	1993
VINGA2	57.631653	11.608792	2009	2020	0.203	-
GÖTEBORG-KROSSHOLMEN (Ringön-Klippan-Torshamnen)	57.691283	11.771256	2021 (1887)	2004B	13.8	1976
STENUNGSUND	58.088461	11.820221	1962	-	-	-
UDDEVALLA	58.346778	11.894472	2010	-	-	-
SMÖGEN	58.353619	11.217850	1910	2002A	0.018	2004
KUNGSVIK	58.996583	11.127250	1976	2005B	7.4	-

Table 1. List of stations with long-term sea level records in the Swedish Sea Level network, operated by Swedish Maritime Administration (SMA), Swedish Meteorological and Hydrological Institute (SMHI), and Chalmers (CTH). Stations in brackets are older discontinued stations located close to the continued station. CGPS marks places where Continuous Global Positioning are installed and measurements of the absolute and levelled land uplift are being carried out. Type of CGPS: A denotes complete stations (EUREF reference stations with antennas placed on solid bedrock), B simplified stations (mounted on buildings). AG means that the station has a platform for observing Absolute Gravity. A complete station list of Swedish sea level stations is presented in Appendix 1.

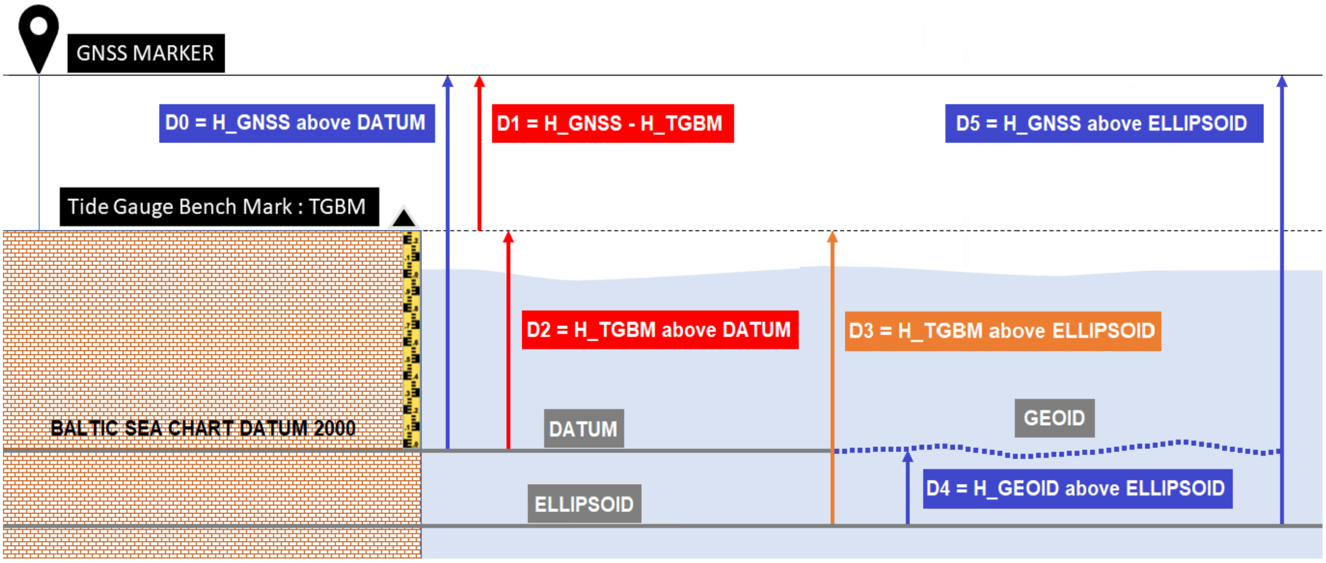

Figure 6. Levelling information of Tide Gauge Bench Mark (TGBM), GNSS Marker and its relationship to the ellipsoid, geoid height and Baltic Sea Chart Datum 2000 (BSCD2000).

International data exchange

All data in the new Swedish Sea Level network are freely available. From an INSPIRE-oriented Open Data Service, it is possible to download the long time series of data (1-minute values in the national height system RH 2000 / BSCD2000 or relative mean sea level). In October 2022, the sea level database at SMHI contained approx. 4900 years with digital sea level observations, where more than 2100 years are from continued stations (Availability Sea Levels Sweden). Most of the data are hourly values, but for the past years, the resolution has been increased to 1-minute values.

Both real-time data and delayed mode data are routinely made available through several national, regional and international programmes (Table 2). Real-time and delayed mode has been screened and quality controlled using the procedures described by IOC-GLOSS, IODE, CMEMS, QUARTOD and others.

Programme	Data host	Frequency	Resolution	Media	Notes
PSMSL	NOC	Yearly	Month	Mail	54 stations
IOC-GLOSS	VLIZ	Hourly	Minute	Web	54 stations
BOOS/NOOS	SMHI	Hourly	Hour	FTP	54 stations
CMEMS	IFREMER	Daily	Hour	FTP	54 stations
EMODNET	SMHI	Daily	Hour	FTP	54 stations
SEADATANET	SMHI	Yearly	Hour	FTP	28 stations
VIVA	SMA	Minute	Minute	Web	60 stations
www.smhi.se	SMHI	Hourly	Minute	Web	60 stations
www.boos.org	DMI	Hourly	Hour	Web	28 stations

Table 2. Sea level data are routinely made available through these programmes. Swedish GLOSS Core Network stations are; Stockholm, and Göteborg-Krossholmen.

Baltic Sea Oceanographic System (BOOS)

The exchange of oceanographic data in the Baltic Sea is very well developed. Within the Baltic Operational Oceanographic System (BOOS), an exchange of in-situ observations between the different institutions on a routinely basis, usually every hour, has been developed. The time resolution of the data is from 1 minute up to one hour, with the highest resolution for sea level data.

Data is mainly used for model assimilation and validation, scientific research, forecasts, warnings and operational use. SMHI is responsible for coordination of the data exchange and to implement routines for real-time quality control, validation and distribution of all sea level data coming from the Baltic Sea. The BOOS station network, consists of about 200 sea level stations (Figure 7).

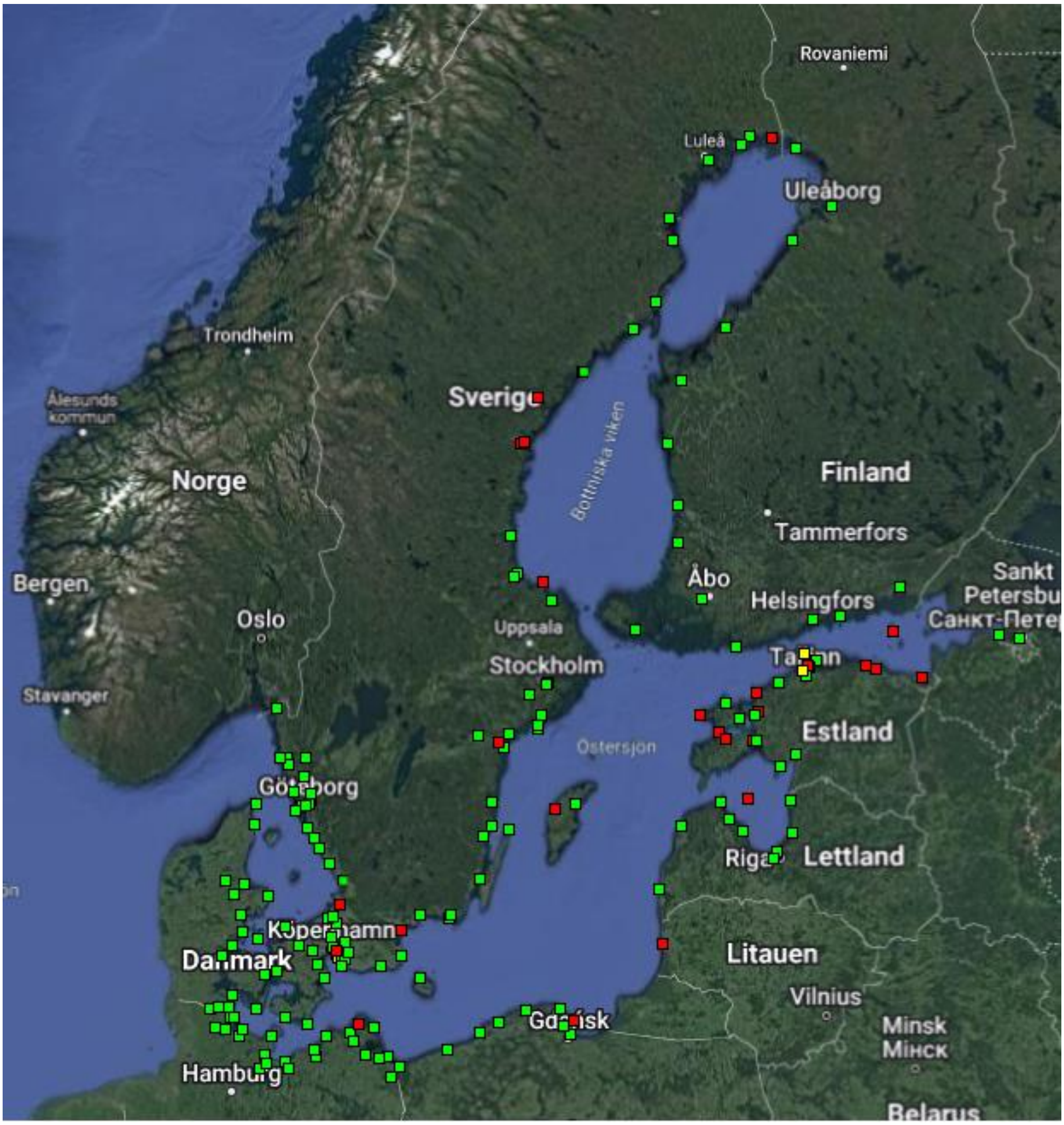

Figure 7. Sea level stations available through the BOOS Community. Stations marked in green are available in near real time. Stations marked in red are not available.

Baltic Sea Hydrographic Commission (BSHC)

The Baltic Sea Hydrographic Commission (BSHC) is an integrant part of the International Hydrographic Organisation (IHO). One task within the BSHC is to implement one common reference level for nautical charts and sea level information. SMA is responsible to coordinate this work within the BSHC Chart Datum, Water level and Currents Working Group.

IHO-BSHC has approved the name and the adoption of the Baltic Sea Chart Datum 2000 (BSCD2000), as the common reference level for all countries surrounding the Baltic Sea. The datum refers to each Baltic country´s realization of the European Vertical Reference System (EVRS) with land-uplift epoch 2000, which is connected to the Normaal Amsterdams Peil (NAP). The national realization´s differs maximum two centimetres to each other. The differences between the calculated mean sea level (MSL) and BSCD2000 at the sea level stations located in the Baltic Sea can be found in this Table.

All data from the Swedish sea level stations will from 3rd June 2019 be presented in the Swedish national survey datum RH 2000 or BSCD2000. In Sweden, the difference between the calculated Mean Sea Level (MSL) in the year of 2021 and BSCD2000 is about +15 cm in the central parts of the Baltic coast and -5 cm in the northern parts of the Swedish west coast (North Sea). An article describing the Swedish transition into the new reference system (Figure 8), for sea level information and nautical charts, is available here.

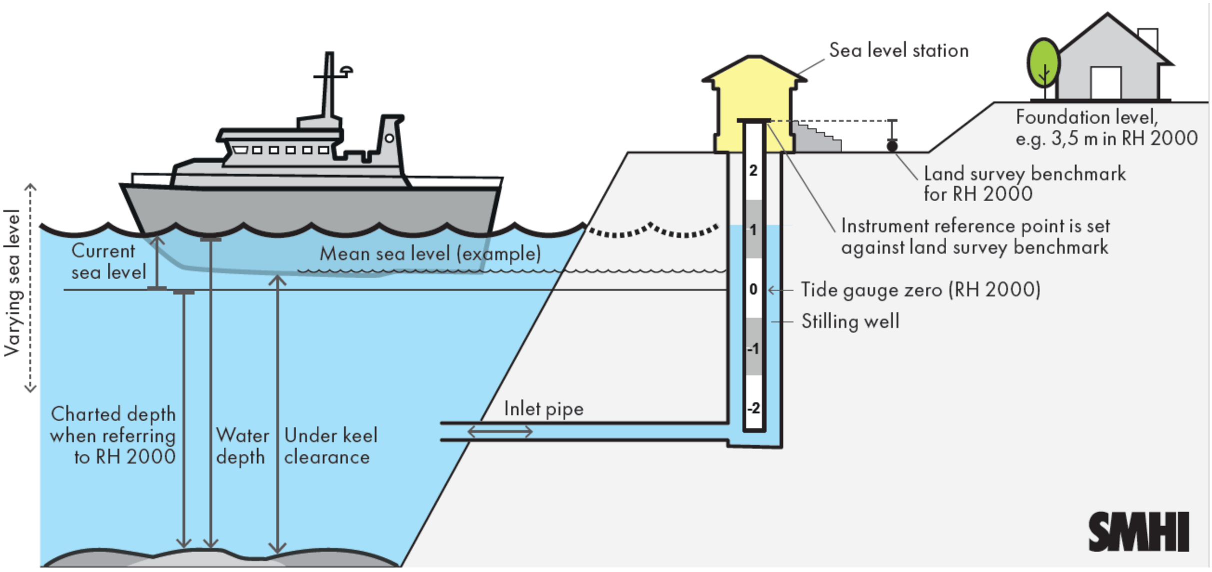

Figure 8. A uniform reference system from land to sea.

IOC Sea Level Station Monitoring Facility

The Intergovernmental Oceanographic Commission (IOC) of UNESCO, in cooperation with the Flanders Marine Institute (VLIZ), provides a service called IOC Sea Level Station Monitoring Facility, which monitors the operational status of global, regional and national networks of real-time sea level stations.

In October 2021, 50 Swedish Sea Level stations (Figure 9) were added to the IOC Sea Level Station Monitoring Facility (news article). One-minute values from a total number of 53 stations are now provided every hour via a Open-data service at the Swedish Meteorological and Hydrological Institute (SMHI).

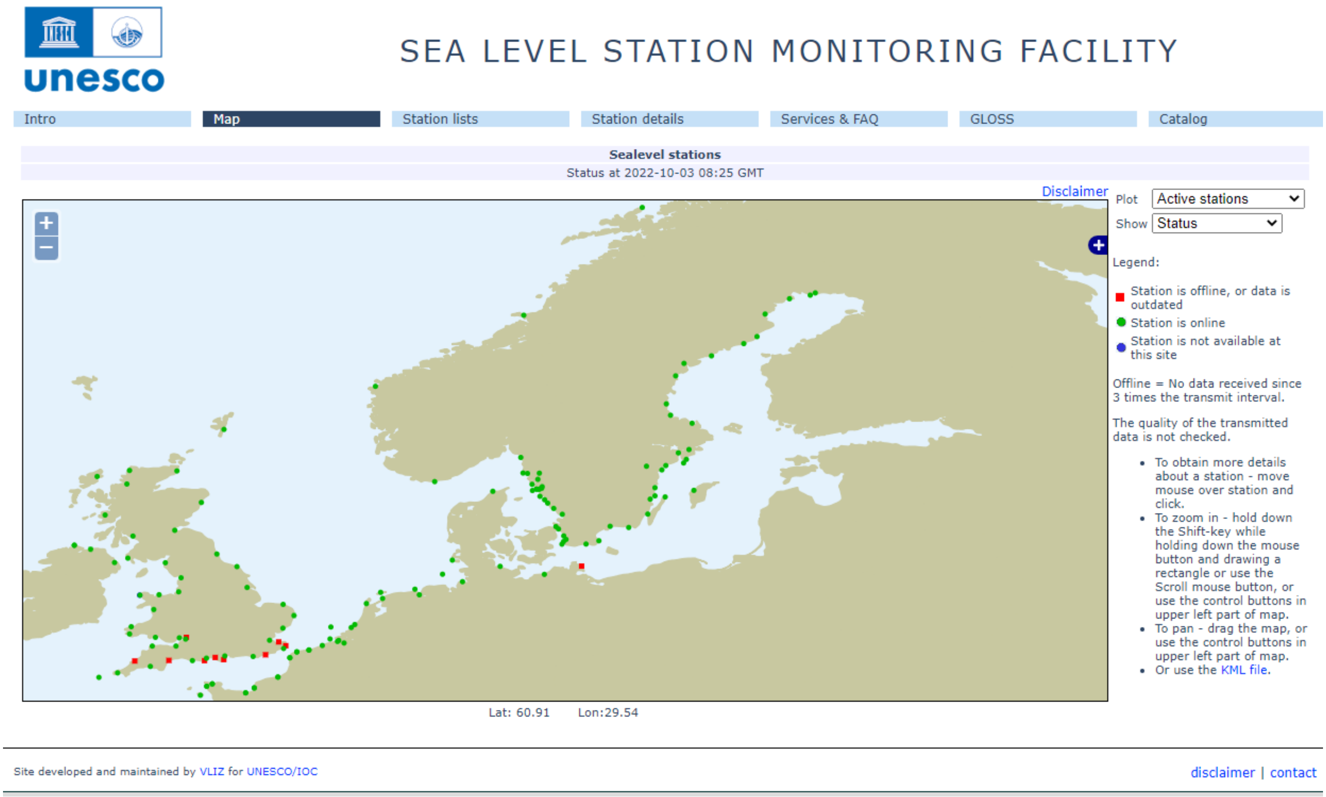

Figure 9. The IOC-UNESCO Sea Level Station Monitoring Facility, operated by Flanders Marine Institute (VLIZ), presents sea level data from 53 Swedish Sea Level stations. Two Swedish stations are Global Sea Level Observing System (GLOSS) Core Network stations; Stockholm and Göteborg-Krossholmen.

"The data presented under this service has not undergone any quality control and data is provided as received. The main objective is to provide a fast status assessment of station availability and performance. The GLOSS data centers at the Permanent Service for Mean Sea Level (PSMSL), the British Oceanographic Data Center (BODC) and the University of Hawaii Sea Level Center (UHSLC) perform the additional processing steps needed to calculate long-term mean sea level (MSL) data at hourly, daily, monthly and yearly averages."

Onsala mareograph

In 2015, a new mareograph (Figure 10) was installed at Råö on the Onsala peninsula, just south of Göteborg. This has been done in close cooperation between SMHI and Chalmers in Göteborg. The station will be located close to a continuous GPS station (A-type), which is operated by Chalmers/SWEPOS. Close to the mareograph, there is also a GNSS-reflectometer (Figure 11) measuring sea level, installed in 2010.

The station is delivering high-resolution (1-minute) values of sea level. A very precise levelling of the station has been performed and the station is very well connected to the national height system RH 2000 or BSCD2000 as for the rest of the locations. The mareograph has been a part of the Swedish Sea Level network (Figure 1 and Appendix 1) since 2015.

Figure 10. The Onsala mareograph, installed in 2015.

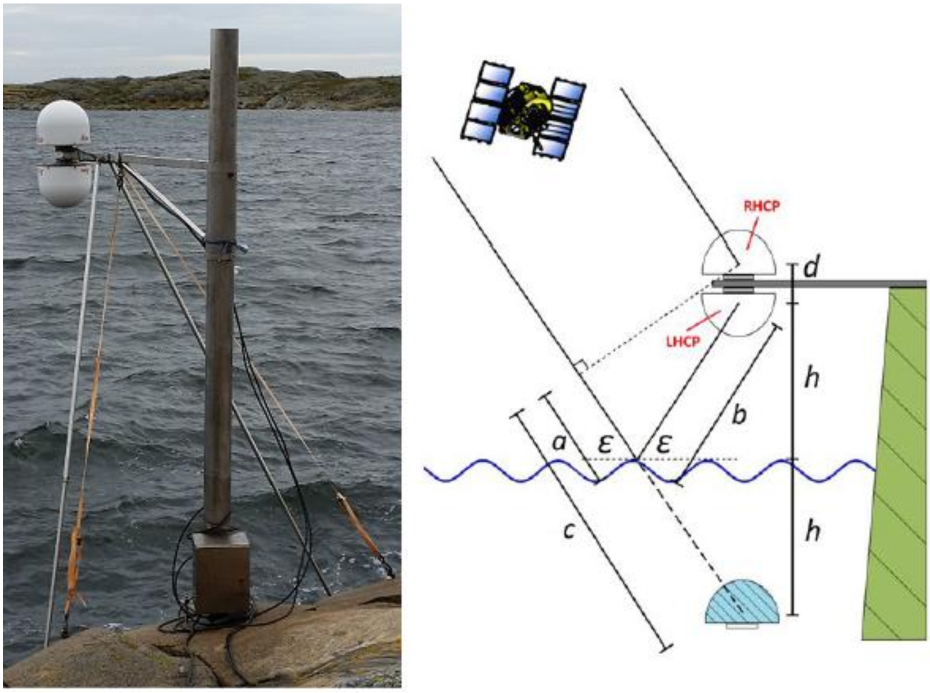

Figure 11. An upward- and downward looking GNSS-reflectometer.

Göteborg-Krossholmen mareograph

In 2021, a new mareograph (Figure 12) was installed at Krossholmen in Göteborg. The station is now delivering high-resolution (1-minute) values of sea level. A very precise levelling of the station has been performed and the station is well connected to the national height system RH 2000, as for the rest of the locations. The mareograph is now a part of the Swedish Sea Level network (Figure 1 and Appendix 1) since May 2021 and will replace Göteborg-Torshamnen as the Swedish contribution to the GLOSS Core Network. Soon, also a Continuous GPS station will be installed nearby, which will be operated by SWEPOS.

Figure 12. The Göteborg-Krossholmen mareograph, installed in 2021.

Stockholm-Skeppsholmen mareograph

In 1889 the Nautical-Meteorological Bureau, a predecessor of SMHI, established a continuously recording sea level station (mareograph) in the bedrock on the island Skeppsholmen, located close to the sluice (Figure 2). This mareograph has since then recorded the Stockholm sea level. The sea level series in Stockholm constitutes the longest sea level record in the world (Figure 3). In 2019, a new measuring chamber and two radar gauges were installed near the old mareograph (Figure 13), which is the new technology for measuring sea level at the site.

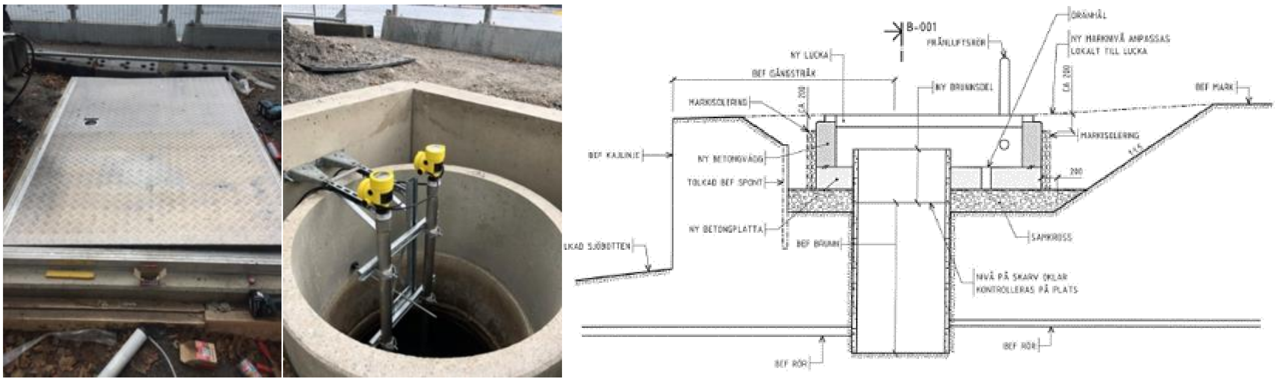

Figure 13. The new measuring chamber with two radar gauges installed.

Appendix 1.

Swedish sea level stations owned and operated by the Swedish Maritime Administration (SMA), Swedish Meteorological and Hydrological Institute (SMHI), Swedish Nuclear Fuel and Waste Management Company (SKB), Chalmers (CTH), Port of Gothenburg (GBG) and University of Gothenburg (GU). Class 1-stations consist of stations with duplicated sensors (two radar sensors or one radar and one pressure sensor), a logger installed at the stations and a battery backup making it possible to re-collect data missing in real-time. Class 2-stations will also have duplicated sensors (one radar and one pressure sensor), including a logger and without battery backup and hence without the possibility to recover data missing in real-time. Class 3-stations will be unchanged and Class 4-stations are discontinued.

STATION	LATITUD	LONGITUD	START YEAR	CLASS
KALIX KARLSBORG (SMA)	65.789258	23.300731	2009	2
KALIX STORÖN (SMHI)	65.697056	23.096014	1974	1
STRÖMÖREN (SMA)	65.548440	22.237952	2016	2
FURUÖGRUND (SMHI)	64.915639	21.230675	1916	1
GÅSÖREN (SMA)	64.663300	21.316700	2009	3
RATAN (SMHI)	63.986042	20.894989	1891	1
HOLMSUND (SMA)	63.695429	20.347527	2009	2
SKAGSUDDE2 (SMA)	63.190519	19.012345	2009	1
LUNDE (SMA)	62.880708	17.876392	2019	2
SPIKARNA (SMHI)	62.363333	17.531111	1968	1
LJUSNE LOTSSTATION (SMA)	61.206944	17.145572	2009	2
BÖNAN (SMA)	60.738310	17.318410	2009	2
FORSMARK (SMHI)	60.408500	18.210850	1975	1
STOCKHOLM (SMHI)	59.324200	18.081700	1889	1
NYNÄS FISKEHAMN (SMA)	58.900667	17.953583	2019	2
LANDSORT NORRA (SMHI)	58.768653	17.858872	2004	1
LANDSORT2 (SMA)	58.744581	17.865014	2009	3
E4 BRON SÖDERTÄLJE (SMA)	59.184712	17.642931	2011	2
OXELÖSUND LOTSSTATION (SMA)	58.661717	17.124750	2009	2
JUTEN (SMA)	58.634180	16.324758	2003	2
ARKÖ (SMHI)	58.483147	16.963647	2015	1
VÄSTERVIK (SMA)	57.748150	16.674700	2009	2
VISBY (SMHI)	57.705833	18.810000	1916	1
SLITE (SMA)	57.639242	18.284503	2009	3
SIMPEVARP (SKB)	57.410278	16.675833	2016	2
ÖLANDS NORRA UDDE (SMHI)	57.366278	17.097228	1851	1
OSKARSHAMN (SMHI)	57.271569	16.479922	1960	2
KALMAR (SMA)	56.658889	16.378333	2009	2
KUNGSHOLMSFORT (SMHI)	56.105194	15.589278	1886	1
KARLSHAMN (SMA)	56.154167	14.821167	2009	2
SIMRISHAMN (SMHI)	55.557611	14.357722	1982	1
YSTAD2 (SMA)	55.422742	13.825672	2014	1

STATION	LATITUD	LONGITUD	START YEAR	CLASS
SKANÖR (SMHI)	55.416789	12.829633	1992	1
KLAGSHAMN (SMHI)	55.522300	12.893628	1929	1
FLINTEN 16 (SMA)	55.560981	12.809542	2009	3
FLINTEN 7 (SMA)	55.589378	12.844475	2009	3
MALMÖ HAMN (SMA)	55.613503	12.997483	2009	2
BARSEBÄCK (SMHI)	55.756400	12.903410	1937	1
HELSINGBORG (SMA)	56.044653	12.687322	2009	2
VIKEN (SMHI)	56.142142	12.579267	1976	1
HALMSTAD (SMA)	56.651267	12.844658	2009	1
FALKENBERG (SMA)	56.892019	12.489455	2014	2
VARBERG2 (SMA)	57.109514	12.241565	2009	2
RINGHALS (SMHI)	57.249756	12.112531	1967	1
ONSALA (CTH)	57.391944	11.918889	2014	1
VINGA2 (SMA)	57.631653	11.608792	2009	2
MÅVHOLMSBÅDAN (GBG)	57.672294	11.707439	2009	4
GÖTEBORG-KROSSHOLMEN (SMHI)	57.691283	11.771256	2021	1
TORSHAMNEN GBG HAMN (GBG)	57.681111	11.788100	2009	4
GÖTEBORG-TORSHAMNEN (SMHI)	57.684667	11.790722	1967	4
TÅNGUDDEN GBG HAMN (SMA)	57.682075	11.872150	2019	2
GÖTEBORG-ERIKSBERG (GBG)	57.696567	11.908833	2012	2
GÖTEBORG-HISINGSBRON (SMA)	57.715039	11.968756	2022	2
GÖTEBORG-TINGSTADSTUNNELN (GBG)	57.723144	11.986922	2012	2
GÖTEBORG-LÄRJEHOLM (GBG)	57.761944	12.003819	2010	*
GÖTEBORG-AGNESBERG (GBG)	57.789775	12.010203	2012	2
JORDFALLSBRON (SMA)	57.855419	12.008650	2009	*
MARSTRAND (SMA)	57.886966	11.593666	2009	2
STENUNGSUND (SMHI)	58.088461	11.820221	1962	1
UDDEVALLA (SMHI)	58.346778	11.894472	2010	1
KRISTINEBERG (GU)	58.250000	11.445833	2012	*
BROFJORDEN (SMA)	58.336007	11.404665	2009	2
SMÖGEN (SMHI)	58.353619	11.217850	1910	1
KUNGSVIK (SMHI)	58.996583	11.127250	1973	1

* Stations not yet included in the network.