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) and Gothenburg harbour (GBG) 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 October 2022.

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 1840-ties 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) 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.

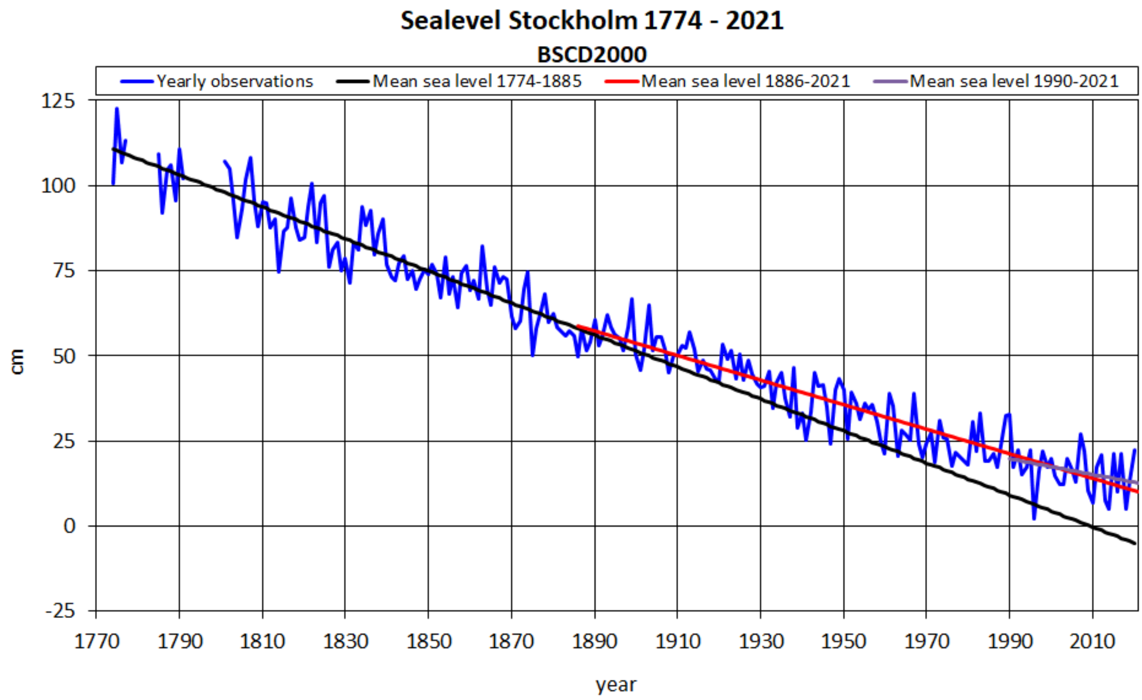

Figure 3. Annual mean sea levels in Stockholm since 1774, with the black, red and purple regression lines corresponding to the land uplift 1774-1885 (0.47 cm/year), 1886-2020 (0.38 cm/year) and 1990-2020 (0.21 cm/year), respectively. The increased sea level rise since the late 19th century appears as 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 30 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.

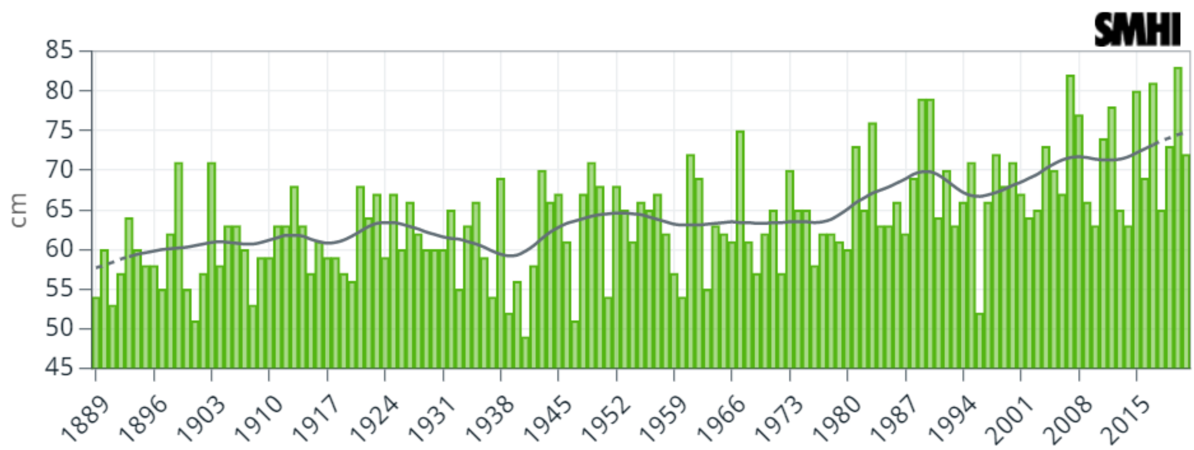

Figure 4. Observed sea level change in Stockholm since 1889. Sea level corrected for the levelled land-uplift (glacial isostatic adjustment). The black line shows the gauss-filtered (smoothed) average.

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 in a database. A software application connected to the database is used for validation and correction of the data. It is also possible to subtract a constant offset to 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 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 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 long time series at SMHI mareograph's, 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 week 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 2021, 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.

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)	Installation of AG
KALIX STORÖN	65.696944	23.096111	1974	-	-	-
FURUÖGRUND	64.915833	21.230556	1916	1993A	9.5	1992
RATAN	63.986111	20.895000	1891	2006A	0.058	2007
SKAGSUDDE2 (Skagsudde)	63.190556	19.012500	2018 (1982)	-	-	-
SPIKARNA (Draghällan)	62.363333	17.531111	1968 (1897)	-	-	-
FORSMARK (Björn)	60.408611	18.210833	1975 (1891)	-	-	-
STOCKHOLM (Nedre Stockholm)	59.324167	18.081944	1889 (1774)	1992A/2013B	15.2/0.373	-
LANDSORT NORRA (Landsort)	58.768889	17.858889	2004 (1886)	-	-	-
ARKÖ (Marviken)	58.484167	16.960556	2014 (1964)	2019B	0.158	-
VISBY	57.639167	18.284444	1916	1993A	5.2	2004
ÖLANDS NORRA UDDE	57.366111	17.097222	1851	2004B	13.5	-
OSKARSHAMN	57.275000	16.478056	1960	-	-	-
KUNGSHOLMSFORT	56.105278	15.589444	1886	2004A	0.108	-
SIMRISHAMN (Ystad)	55.557500	14.357778	1982 (1886)	-	-	-
YSTAD2 (Ystad)	55.416667	13.816667	2014 (1886)	2011B	2.170	-
SKANÖR (Ystad)	55.416667	12.829722	1992 (1886)	2002B	1.8	-
KLAGSHAMN (Malmö)	55.522222	12.893611	1929 (1924)	-	-	-
BARSEBÄCK	55.756389	12.903333	1937	2002B	5.9	-
VIKEN	56.142222	12.579167	1976	-	-	-
RINGHALS (Varberg)	57.249722	12.112500	1967 (1886)	1991A	19.7	1993
ONSALA (Varberg)	57.391944	11.919167	2015 (1886)	1993A/2012B	0.533/0.496	1993
GÖTEBORG-KROSSHOLMEN (Göteborg-Torshamnen)	57.691316	11.771246	2021 (1967)	-	-	-
GÖTEBORG-TORSHAMNEN (Göteborg Ringön-Klippan)	57.684722	11.790556	1967 (1887)	2004B	12.8	1976
STENUNGSUND	58.093333	11.832500	1962	-	-	-
UDDEVALLA	58.347500	11.894722	2010	-	-	-
SMÖGEN	58.353611	11.217778	1910	2002A	0.018	2004
KUNGSVIK	58.996667	11.127222	1976	2005B	7.4	-

Table 1. List of stations in the Swedish Sea Level network, operated by Swedish Meteorological and Hydrological Institute (SMHI), Swedish Maritime Administration (SMA) 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.

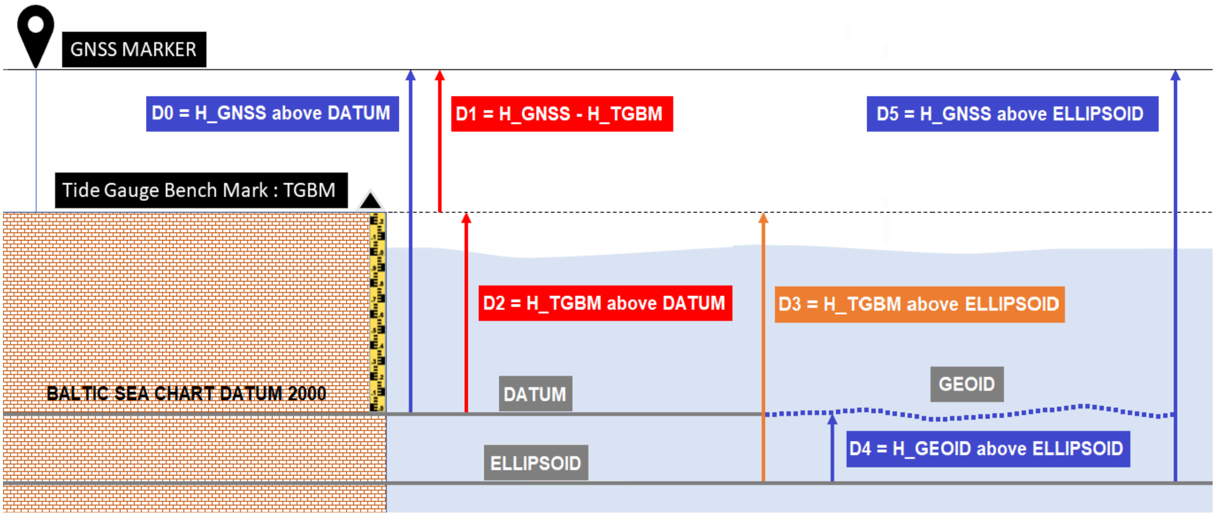

Figure 6. Levelling information of Tide Gauge Bench Mark (TGBM), GNSS Marker and its relationship to the ellipsoid, geoid height and Baltic Sea Chart Datum 2000 (BSCD2000).

International data exchange

All data in the new Swedish Sea Level network are freely available. From an INSPIRE-oriented web-site 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. 5000 years with digital sea level observations, where more than 3000 years are from continued stations, including the sea level stations operated by SMA. 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	53 stations (28 SMHI, 25 SMA)
IOC-GLOSS	VLIZ	Hourly	Minute	Web	53 stations (28 SMHI, 25 SMA)
BOOS/NOOS	SMHI	Hourly	Hour	FTP	53 stations (28 SMHI, 25 SMA)
CMEMS	IFREMER	Daily	Hour	FTP	53 stations (28 SMHI, 25 SMA)
EMODNET	SMHI	Daily	Hour	FTP	53 stations (28 SMHI, 25 SMA)
SEADATANET	SMHI	Yearly	Hour	FTP	28 stations (28 SMHI)
VIVA	SMA	Every minute	Minute	Web	60 stations (28 SMHI, 32 SMA)
www.smhi.se	SMHI	Hourly	Minute	Web	60 stations (28 SMHI, 25 SMA)
www.boos.org	DMI	Hourly	Hour	Web	28 stations (28 SMHI)

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 data 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 several hours, with the highest resolution for sea level data.

Data is mainly used for model assimilation and validation, forecasts and warnings, scientific research and for 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).

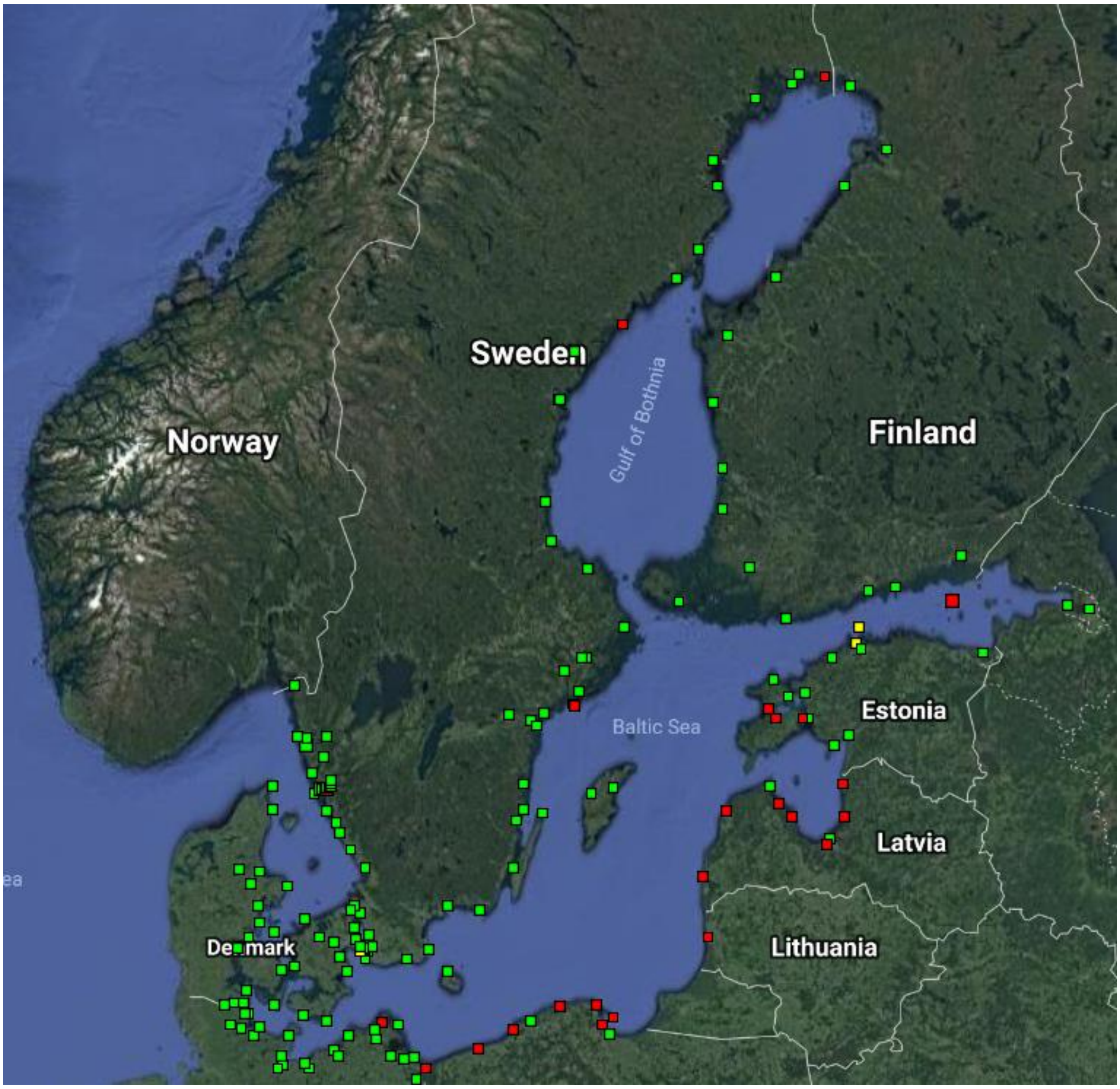

Figure 7. Sea level stations available through the BOOS Community. Stations marked in green are available in near real time. Stations marked in red are not available for different reasons.

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 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). A fact sheet describing the Swedish transition into the new reference system (Figure 8), for sea level information and nautical charts, is available here.

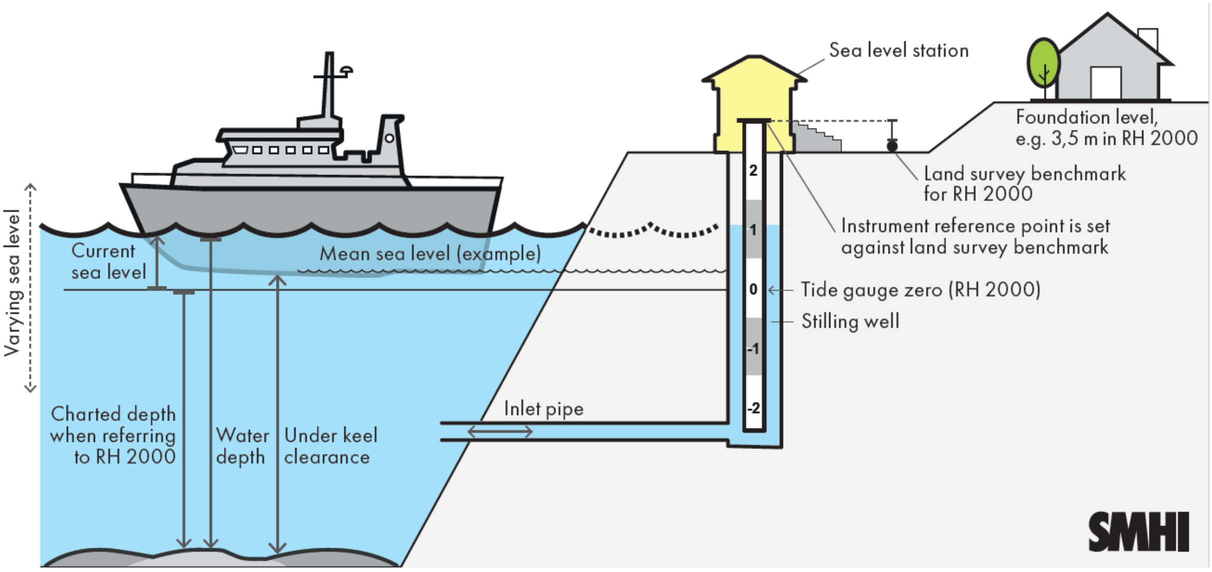

Figure 8. A uniform reference system from land to sea.

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).

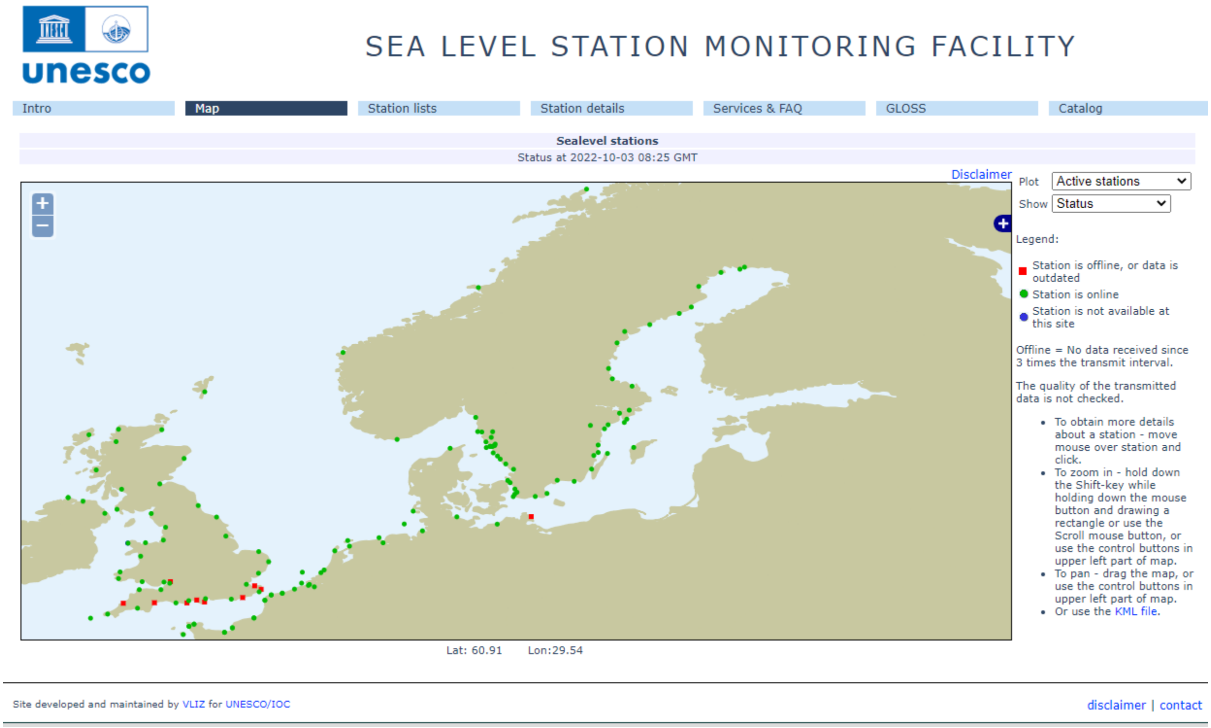

Figure 9. The IOC-UNESCO Sea Level Station Monitoring Facility, operated by Flanders Marine Institute (VLIZ), presents sea level data from 53 Swedish Sea Level stations. Two Swedish stations are Global Sea Level Observing System (GLOSS) Core Network stations; Stockholm and Göteborg-Krossholmen.

"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 now 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.

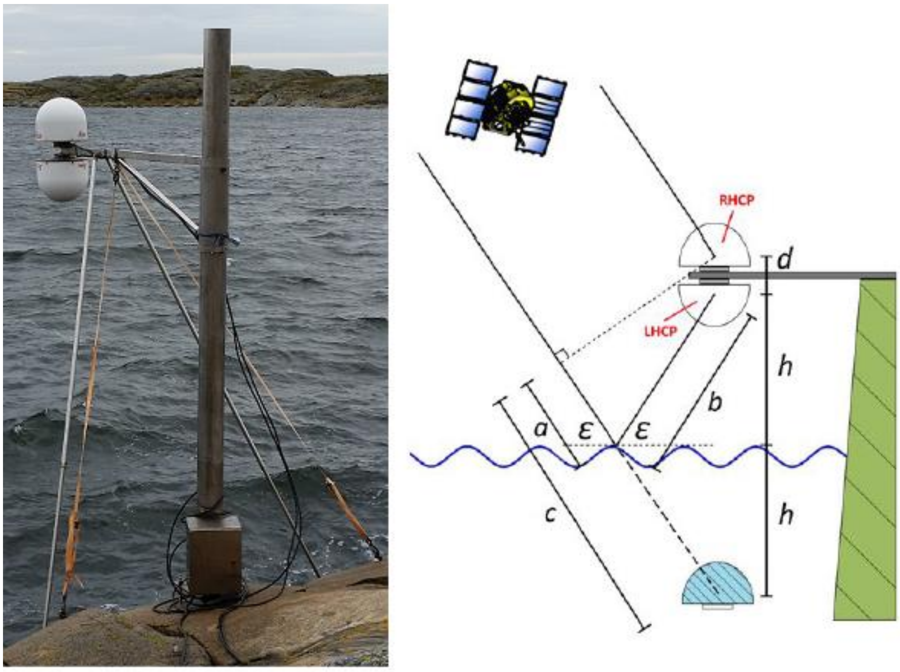

Figure 11. An upward- and downward looking GNSS-reflectometer.

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.

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), Gothenburg harbour (GBG) and Gothenburg University (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 will be dismantled.

STATION	LATITUD	LONGITUD	START YEAR	CLASS
KALIX KARLSBORG (SMA)	65.788889	23.303333	2009	2
KALIX STORÖN (SMHI)	65.696944	23.096111	1974	1
STRÖMÖREN (SMA)	65.549722	22.238333	2016	2
FURUÖGRUND (SMHI)	64.915833	21.230556	1916	1
GÅSÖREN (SMA)	64.678611	21.249167	2009	3
RATAN (SMHI)	63.986111	20.895000	1891	1
HOLMSUND (SMA)	63.695833	20.347222	2009	2
SKAGSUDDE2 (SMA)	63.190556	19.012500	2009	1
LUNDE (SMA)	62.880556	17.876389	2019	2
SPIKARNA (SMHI)	62.363333	17.531111	1968	1
LJUSNE ORRSKÄRSKAJEN (SMA)	61.206944	17.145556	2009	2
BÖNAN (SMA)	60.738611	17.318611	2009	2
FORSMARK (SMHI)	60.408611	18.210833	1975	1
STOCKHOLM (SMHI)	59.324167	18.081944	1889	1
NYNÄS FISKEHAMN (SMA)	58.917500	17.972222	2019	2
LANDSORT NORRA (SMHI)	58.768889	17.858889	2004	1
E4 BRON SÖDERTÄLJE (SMA)	59.184722	17.642778	2011	2
OXELÖSUND VINTERKLASEN (SMA)	58.661667	17.124722	2009	2
JUTEN (SMA)	58.634167	16.324722	2003	2
ARKÖ (SMHI)	58.484167	16.960556	2015	1
VÄSTERVIK (SMA)	57.748333	16.675278	2009	2
VISBY (SMHI)	57.705833	18.810000	1916	1
SLITE (SMA)	57.639167	18.284444	2009	3
SIMPEVARP (SKB)	57.410278	16.675833	2016	2
ÖLANDS NORRA UDDE (SMHI)	57.366111	17.097222	1851	1
OSKARSHAMN (SMHI)	57.275000	16.478056	1960	2
KALMAR (SMA)	56.658889	16.378333	2009	2
KUNGSHOLMSFORT (SMHI)	56.105278	15.589444	1886	1
KARLSHAMN (SMA)	56.154167	14.821389	2009	2
SIMRISHAMN (SMHI)	55.557500	14.357778	1982	1
YSTAD2 (SMA)	55.416667	13.816667	2014	1

STATION	LATITUD	LONGITUD	START YEAR	CLASS
SKANÖR (SMHI)	55.416667	12.829722	1992	1
KLAGSHAMN (SMHI)	55.522222	12.893611	1929	1
FLINTEN 16 (SMA)	55.561111	12.809444	2009	3
FLINTEN 7 (SMA)	55.589444	12.844444	2009	3
MALMÖ HAMN (SMA)	55.613611	12.997500	2009	2
BARSEBÄCK (SMHI)	55.756389	12.903333	1937	1
HELSINGBORG (SMA)	56.044722	12.687222	2009	2
VIKEN (SMHI)	56.142222	12.579167	1976	1
HALMSTAD (SMA)	56.648889	12.835833	2009	1
FALKENBERG (SMA)	56.891944	12.489444	2014	2
VARBERG2 (SMA)	57.111111	12.238611	2009	2
RINGHALS (SMHI)	57.249722	12.112500	1967	1
ONSALA (CTH)	57.391944	11.919167	2014	1
VINGA2 (SMA)	57.631667	11.608889	2009	2
MÅVHOLMSBÅDAN (SMA)	57.672222	11.707500	2009	3
GÖTEBORG-KROSSHOLMEN (SMHI)	57.691316	11.771246	2021	1
GÖTEBORG-TORSHAMNEN (SMHI)	57.684722	11.790556	1967	4
TÅNGUDDEN GBG HAMN (SMA)	57.681944	11.872222	2019	2
GBG-ERIKSBERG (GBG)	57.696667	11.908889	2012	2
HISINGSBRON GBG HAMN (SMA)	57.714722	11.967222	2022	2
GÖTEBORG-GÖTAÄLVBRON (GBG)	57.714444	11.967500	2010	*
GÖTEBORG-TINGSTADSTUNNELN (GBG)	57.723056	11.986944	2012	2
GÖTEBORG-LÄRJEHOLM (GBG)	57.765833	12.005556	2010	*
GÖTEBORG-AGNESBERG (GBG)	57.789722	12.010000	2012	2
MARSTRAND (SMA)	57.886944	11.593611	2009	2
STENUNGSUND (SMHI)	58.093333	11.832500	1962	1
UDDEVALLA (SMHI)	58.347500	11.894722	2010	1
KRISTINEBERG (GU)	58.250000	11.450000	2012	*
BROFJORDEN (SMA)	58.336111	11.404722	2009	2
SMÖGEN (SMHI)	58.353611	11.217778	1910	1
KUNGSVIK (SMHI)	58.996667	11.127222	1973	1

* Stations not yet included in the network.