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Adjustment of the European Vertical Reference System for the representation of the Baltic Sea water surface topography

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Abstract
Reference system was adapted EVRS (European Vertical Reference System), which is based on the level of NAP (Normal Amsterdam Peil) for the spatial imaging extreme levels of the Baltic Sea. The observational data on sea levels have been converted of the selected 38 stations in each of the Baltic countries to the level of NAP (Normal Amsterdam Peil). The images of the Baltic Sea area were obtained in a uniform reference system, for the example of chosen stormy situation of 1–2 November 2006, and the spatial distribution of the maximum and no maximum sea levels that occurred during the 1960–2010 year.

Introduction

Users of navigational information, hydrographers and oceanographers confirm difficulties in interpreting bathymetric charts of the Baltic Sea and in presenting sea level oscillations in storm surges. This is due to the absence of one common geodetic reference system for sea level observations in individual states of the Baltic region.

In June 2005 the International Hydrographic Organization and the Baltic Sea Hydrographic Commission established a Chart Datum Working Group for the harmonization of reference levels of Baltic Sea charts. The main task of this working group was to examine possibilities of utilizing the European Vertical Reference System (EVRS) as main alternative for vertical reference systems on Baltic Sea charts. Another task of this group was to set timetables and preliminary conditions in collaboration with each Baltic state which wishes to use a harmonized datum on its sea charts. The Chart Datum WG should prepare recommendations indicating how the sea level variations should be shown on paper and electronic navigational charts and in other navigational publications.

The Baltic Sea Hydrographic Commission had analyzed geodetic networks of individual Baltic states and found that respective sea levels should be referred to one datum, that is Normaal Amsterdams Peil (NAP), that is Amsterdam Ordnance Datum, which is the reference level in the EVRS. This system was created after standardizing the United European Leveling Network in which various leveling networks, GPS and mareographic data have been combined.

This work aims at adapting the EVRS system based on the NAP datum, for spatial presentation of extreme levels of the Baltic Sea. We have found that observation data of sea levels from particular Baltic states can be converted to the NAP, which will bring an image of the Baltic surface in a standardized reference system.

The definition of the European Vertical Reference System

EVRS is related to the Earth's gravity field and defined as follows [1]:

- the reference surface is a horizontal surface for which the potential of gravity W_0 is constant:

$$W_0 = W_{0E} = \text{const.} \tag{1}$$

  and which is at the Normaal Amsterdams Peil (NAP) level;

- vertical components are differences ΔW_P between the potential W_P of the Earth gravity field at a selected point *P* and a potential W_{0E} of the EVRS datum. The potential difference (ΔW_P) is also called the geopotential number *Cp*:

$$-\Delta W_p = Cp = W_{0E} - W_p \quad (2)$$

Normal heights are equivalent to geopotential numbers;
- EVRS is a system in which tidal datum system has been adjusted according to the resoulution of the International Association of Geodesy. The datum of the EVRS is realized by the NAP. Consequently the geopotential number of a NAP level is also equal to zero:

$$C_{\mathrm{NAP}} = 0; \quad (3)$$

- parameters and constants defining the vertical system are parameters and constants defined by Geodetic Reference System 1980 (GRS-80). As a result of adopting of such parameters and constants, the normal potential W_{NAP} at a NAP point is normal potential of the GRS-80 ellipsoid:

$$W_{\mathrm{NAP}}^{\mathrm{REAL}} = U_{\mathrm{OGRS80}} \quad (4)$$

- the EVRF-2000 system is realized by the geopotential number and a corresponding normal height of the reference point number 000A2530/13600 of the UELN network;
- the gravity field potential at the NAP can be calculated from this relation:

$$W_{\mathrm{NAP}} = W_0 + \Delta W_{\mathrm{SST}} + \Delta W_{\mathrm{TG0}} \quad (5)$$

where the notations are those presented in figure 1.

Historical outline of vertical reference systems in the Baltic states and methods of measurement data conversion

Principally, in all Baltic states vertical reference levels have been based on local mean sea levels (MSL). However, different methods are used for obtaining mean sea levels in various countries, thus methods of establishing the datum were different. This is related to the existing differences in geodetic reference systems in these countries. Only the practical realization of the United European Leveling Network that started in 2005 allowed to find the relations between that network and the NAP. At present it is possible to adopt a standard EVRS system based on the NAP level and to convert all previous and current sea level observations from mareographs and water gauges located in the Baltic states. The historical outline given below focuses on vertical reference systems in particular countries and illustrates the way to the standardization of data.

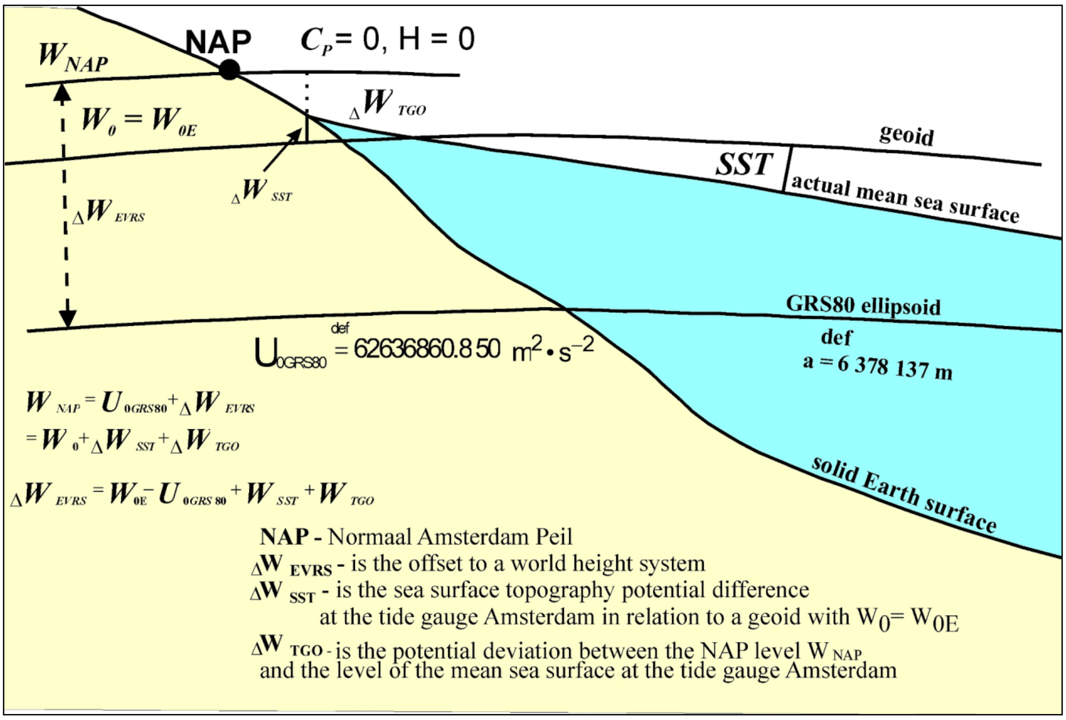

Fig. 1. Relations between the EVRS definition in the global vertical system and its practical realization EVRF 2000 [2]

Germany

There are two reference systems in Germany due to the existence of two German states after World War II. One is the *Normall-Null* system and is binding in Schleswig-Holstein land. The datum of this system has always been related to with NAP. The other system HN (Höhen Null) is in use in Mecklenburg-Vorpommern and is related to the Kronstadt datum. HN-14 cm level is a MSL for most water gauge stations of that region.

From the beginning of the 19th century Germany had one standard datum used in official measurements: normal zero (NN) which is referred to the long-term mean level at the Amsterdam water gauge. The system is still in use in Schleswig-Holstein Land. However, in the years 1912–1945 the system was converted from the old one (*alte system* – NN a.S.) into the new system (*neue system NN n.S*). The diffrence between the two systems is slight and for individual stations does not exceed a few centimeters [3].

Within the territory of the former German Democratic Republic in 1976 a new system of height measurement was introduced: *Normal-Höhen-system* (HN76), whose reference is not the long-term mean sea level of the Amsterdam gauge, but the one located in Kronstadt (near St. Petersburg). On the coasts of today's Mecklenburg-Vorpommern from 1910 to November 1985 NN a.S. system was in use. The water gauge datum was at a level NN –5.00 m. Since 1 November 1985 00:00 of Central European Time water level measurements have been based on the HN76 system which is not in line with the long-term mean sea level for the Baltic on the coasts of Mecklenburg-Vorpommern. For this reason, to compare the data of sea level measured in the two systems the relations shown in figure 2 should be used.

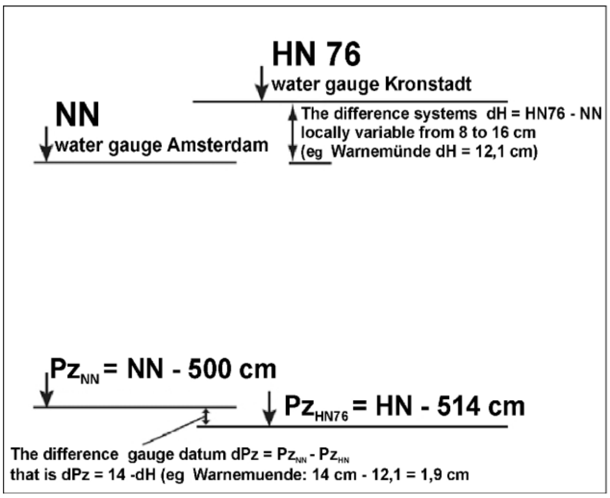

Fig. 2. Differences height reference systems [4]

Conversion to the NN system

W [cm NN] = W [cm HN] + dH [cm]

W [cm NN] = W [cm Pz_{HN}] – 514 cm + dH [cm]

W [cm Pz_{NN}] = W [cm Pz_{HN}] – dPz [cm]

dPz [cm] = 14 – dH

An example transformation of water levels at Warnemünde gauge station from HN_{76} to NN

$$W_{HN} = 546 \text{ cm},$$

$$W_{NN} = W_{HN} - 14 \text{ cm} + \text{dH} \tag{6}$$

where: dH – local difference in the reference systems (Table 1),

$$W_{NN} = 546 - 14 + 12.1 = 544 \text{ [cm] NN}$$

Table 1. Difference in German water gauge zero levels of the German systems [5]

Water gauges	Local difference in the reference systems HN – NN = dH	The value that was reduced to the water gauge on 01.11.1985 (the difference gauge datum) dPz
Wismar	9.8 cm	4.2 cm
Warnemünde	12.1 cm	1.9 cm
Sassnitz	11.0 cm	3.0 cm
Greifswald	12.0 cm	2.0 cm
Koserow	9.7 cm	4.3 cm

Introduced in 2000, NHN (*Normalhöhennull*) is a new German Mean Height Reference System used by German geodetic services and height networks DHHN92. This level is also based on the NAP. At the same time the NHN level is a basis for UELN and is compatible with EVRF2000. NHN was introduced because at heights based on *Normalnull* the real gravitational field of the Earth was not taken into account. The method of calculating heights has been changed. NHN in the future will be a reference level for all sea water gauges in Germany, and consequently, the datum for navigational charts.

This study makes use of sea level data from water gauges of Mecklenburg-Vorpommern Land: Wismar, Warnemünde Sassnitz, Greifswald, Koserow (heights of water gauge datums Pz = HN – 5.14 m) and from Schleswig-Holstein Land: Schleimünde (Pz = –4.99 NHN), Kiel (Pz = –5.00 NHN), Heiligenhafen (Pz = –4.98 NHN, Travemünde (Pz = –5.01 NHN).

All data have been referred to the NAP (Pz = 0.00 NN) (Table 2).

For this purpose the above formulas of conversion into the NN system (formula 1) have been used for water gauges working in the NH76 system (Mecklenburg-Vorpommern) for data from 1 November 1985. Then, for the whole observation series of hourly values of sea levels the value 500 has been subtracted to determine one ordinate of water gauge zero (0.00 NN).

Sea level data from the water gauge stations in Schleswig-Holstein, which had already been operating in the NN system, have been brought to one ordinate PN = –5.00 NN (according to corrections from table 2), then from the whole observation series the value 500 was subtracted to define one ordinate of the water gauge zero (0.00 NN)

Table 2. Corrections adjusting the ordinate of a water gauge in the NN system

The water gauge	Zero level with respect to NN [cm]	Correction [cm]
Schleimünde	–499	+1
Kiel	–500	0
Heiligenhafen	–498	+2
Travemünde	–501	–1

Denmark

Till the year 2002 a commonly binding vertical reference system was *Dansk Normal Nul* (DNN). It was established as a joint reference level for the whole country, for the first precise leveling network that covered main geodetic series at the turn of the 20th century. DNN is a mean value of mean sea levels measured in 1885–1904 for ten ports located throughout the country. These included ports on Jutland (Frederikshavn, Hirtshals, Aarhus, Fredericia, Esbjerg) on Fyn – Slipshavn, on Zealand (Korsor, Hornbæk, Copenhagen) and on Falster island – the port of Gedser. The DNN level is physically represented by a mark on the door of Aarhus cathedral at a height of 5.6150 m. This is the reference point for all heights measured at DNN. The full name of the system, DNN GM 1891, is derived from the name of the first precise leveling network. The second precise leveling network in Denmark was realized by the Institute of Geodesy in 1940–1953 in order to improve the relations of local heights on Zealand with local height on Fiona and Jutland. Modifications of the system were called DNN GI 1944. That system was introduced on the islands of Zealand, Lolland, Falster, Mon and Fyn, while it was never commonly used on Jutland, where DNN GM continued to be in use. The second precise leveling network was not based on new measurements of sea level and the old reference level remained, established 40 years earlier.

The communes of Copenhagen and Frederiksberg have their own vertical reference system – Københavns Nul (KN) – Copenhagen Zero, the oldest reference system in Denmark, introduced as early as 1846. Copenhagen Zero is based on sea level measurements from the period 1817–1832. Later levelings (the latest in 1977) were related to new water level measurements. Copenhagen Zero is not equal to the elevation of the datum in DNN, because the two points were not established at the same time and ports.

On the majority of small Danish islands without a land link to the continent a datum is established by means of local measurements of sea levels taken over shorter periods of observation. The so called Local Null (LN) is a mean sea level in a local port [6, 7].

Due to isostatic movements after the last glaciation a relative increase in sea level is recorded along the most part of the Danish coast (south of Hirtshals – Helsingør line). Over the past 100 years the sea level in Denmark has increased from –2 cm to 13 cm. The largest relative rises of sea level were observed on the southern and south-western Jutland, while the lowest increases were observed on northern Jutland and Zealand [8]. Due to those changes a common reference point had to be established for elevations and current mean sea level. As a result of measurements of mean sea level in the ten above mentioned ports in 1990 and the third precise leveling network realized in the years 1982–1994, a new uniform reference system *Dansk Vertikal Reference 1990* (DVR 90) was established and introduced in May 2002. Its reference point on land, like in DNN system, is a mark on the Aarhus cathedral door, but placed at the raised height now equal to 5.570 m. The difference between the two systems (DNN – DVR90) oscillates from +2 cm (northern Jutland) to – 14 cm (southern Jutland) [9]. The system DVR90 by the updating of the national geoid model enables estimation of heights above sea level by GPS with one-digit centimeter accuracy. From 1 January 2006 DVR90 replaced all previous reference systems. We should be aware, however, that there exist various reference systems on older maps and in documents according to which depths and heights are measured and calculated. For this reason, there are clear recommendations of the national geodesic service, *Geodatastyrelsens,* to include information on maps about used the vertical reference system [7].

Denmark will continue to use DVR90 in the future. DVR90 is related to the geodesic vertical reference and differs by only two centimeters from the NAP. Therefore, there is no reason to make any changes in the present system.

For the purpose of this study we have obtained series of hourly sea levels from *Danmarks Meteorologiske Institut* for water gauge stations

Table 3. Corrections for the conversion of observation data from the system of local datum to the system DVR90 and from the system DVR90 to the system EVRS for selected ports in Denmark (cm)

The water gauge	Geographical coordinates	Correction from the system of local datum to the system DVR90 [cm]	Correction from the system DVR90 to the system EVRS 2000 (NAP) [cm]
Hornbæk	56.09500 N, 12.45833 E	–1.8	+2
Gedser	54.57999 N, 11.92166 E	–5	+2
Frederikshavn	57.43500 N, 10.54833 E	–3	+2
Aarhus	56.15000 N, 10.22833 E	–3	+1
Fynshav	54.99526 N, 09.98610 E	–17	+1
Korsor	55.32833 N, 11.13000 E	–6	+2
Drogden	55.53333 N, 12.70221 E	–2	+2

Frederikshavn, Aarhus, Hornbæk, Fynshav, Korsor, Drogden, Gedser. The data have been referred to the LN system (local datum). To make the data comparable with data from other Baltic states, the sea levels were converted into the DVR90 system, then to one ordinate of the NAP water gauge datum, using transformations of national reference systems to standards of the European Vertical Reference System 2000 [10]. Details of conversions are given in table 3.

Sweden

The first systematic height measurement in Sweden was performed in 1857–1885, and measurement results were recorded in the RH system (*Rikets Höjdsystem*) 1860. Soon afterwards the system was replaced by RH 00, a new system based on the first Swedish precise leveling network, realized in 1886–1905 by the Swedish General Headquarters. The mean water level in Stockholm in 1900 was chosen as the datum. The reference point of the datum is located on Knights' Island in the center of Stockholm at a height of 11.80 meters above sea level. Another vertical reference system in Sweden was RH 70, based on the second precise leveling in Sweden realized in 1951–67. The system adopted a new datum – NAP, which is also a datum reference level for other European countries. The land based reference point for the new datum in Sweden is a solid benchmark mounted in a granite rock in the seaside village of Varberg (south-western Sweden). The height of this point is 4.234 meters above NAP [11].

In 2005 Sweden introduced a new national vertical reference system *Rikets Höjdsystem* 2000 (RH 2000). It was the outcome of the third precise leveling in Sweden, with relevant measurements performed in 1979–2003. The RH 2000 system was defined as Swedish realization of EVRS. It implies the following relationships [12, 13]:

- the system datum is defined as Normaal Amsterdams Peil (this is the geopotential number resulting from the latest definition of EVRF 2000);
- the system takes into account isostatic movements of the land; the reference period for the reduction of post glacial movement estimates is the year 2000;
- isostatic movement corrections in the system are made via the NKG2005LU model, whose construction was managed by the Nordic Geodetic Commission.

The system RH2000 can be used for the regulation of the Baltic Leveling Ring.

Isostatic movements are an essential problem in the recording sea level in Scandinavia. In the north of the Scandinavian Peninsula the Earth crust rises at a rate of 1 cm/year as a response to a gradual extinction of heavy ice caps formed 10 000 years ago. Land movement is much slower in the south of Scandinavia than in the north [14]. *Sveriges Meteorologiska och Hydrologiska Instytut*, the operator of water gauge network in Sweden, uses the RH 2000 system, which takes into account isostatic movements in sea level measurements. Besides, observation series of sea levels recorded in the system as annual means are corrected every year by the absolute land uplift for each water gauge station. MSL 2000 (RH 2000) in Sweden has become a datum on newly produced charts. Before 1994 MSL was a reference level for a given current year. MSL 2000 is defined as a mean longterm sea level for each water gauge station managed by the Swedish Meteorological and Hydrological Institute [15].

The equation below describes correction and adjustment of sea level used at SMHI [16]:

$$AW\ (yy) = HW\ (yy) - a \cdot (yy - 1886) + \text{coefficient of correction} \tag{7}$$

where:

AW – corrected, annual mean sea level;

HW – annual mean sea level (cm) in a local (unique) reference system for each water gauge station;

yy – current year;
a – absolute land uplift (cm/year) for each water gauge station;
coefficient of correction – a numerical coefficient established so that the trend line of linear regression of corrected sea levels intersects the datum in 1886. The year 1886 marks the origin of sea level recordings for 14 Swedish water gauge stations.

The authors of this study have received from the Swedish Meteorological and Hydrological Institute hourly values of sea levels as well as maximum mean and minimum values recorded in a given year in the system RH 2000, and values corrected for the land crust movements. These data come from the following water gauge stations: Furuögrund, Klagshamn, Kungsholmsfort, Landsort, Ratan, Smögen, Stockholm, Ystad-Skanör. All analyses in this study are made on the basis of data corrected by the land movement for each year (so called mean water).

Finland

In Finland the mean sea level (MSL) is the vertical reference system for navigational charts. The Finnish Institute of Marine Research publishes the official mean water (theoretical water) every year. The determination of the theoretical water is based on long-term observations from 13 mareographs distributed along the Finnish coast (Fig. 3). Mareographs are related to the national height measurement service according to which the reference level is different than MSL used on navigational charts.

Finland can change the system based on theoretical predicted mean sea level to EVRF 2000. One of the reasons is that isostatic movements of the Earth crust continuously change depths along the Finnish coast. Another reason is that due to certain oceanographic phenomena a long period of variation in mean sea level has not been linear over the past several years as was the case earlier. This means that for a longer periods it is no longer possible to make a reliable forecast of mean sea level.

Theoretical sea level is the time-dependent prediction of an expected value of long-term mean sea level delivered five years in advance by the Finnish Institute of Marine Research. We can see in figure 3 that theoretical mean sea level ran close to 15-year moving mean till 1980 but later forecasts of the theoretical mean sea level became increasingly difficult. Therefore, the theoretical sea level has lost its value and usefulness as a vertical reference level in Finland. The Finnish maritime administration has stated that charts of the Finnish coast would be based in the future on EVRF2000 [15].

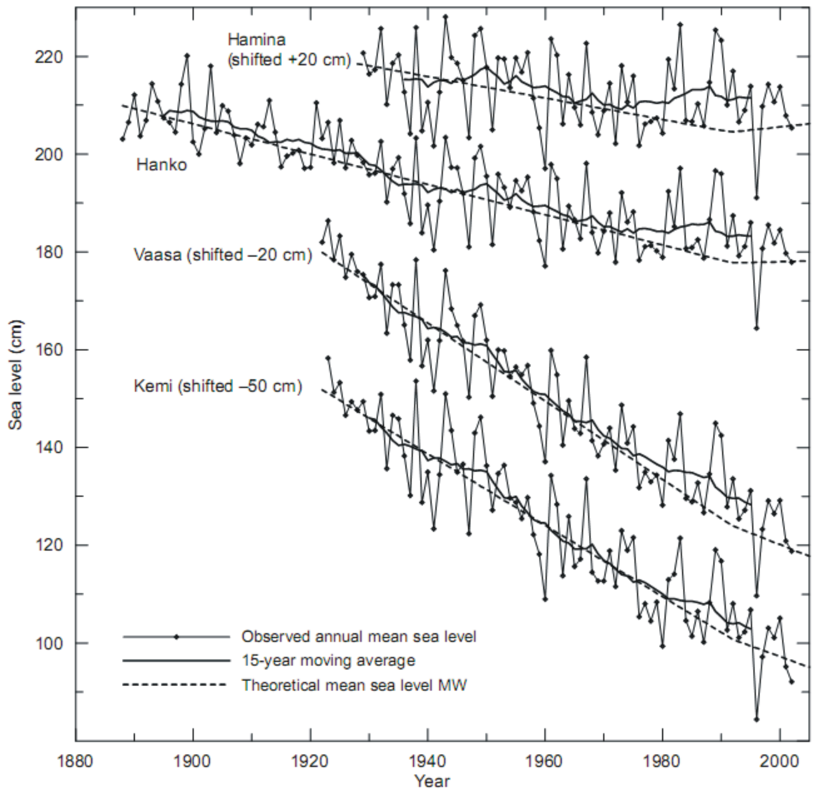

Fig. 3. Observed yearly mean values, 15-year moving average and theoretical mean sea level for selected mareographs along the Finnish coast [17]

Table 4. Selected measurement characteristics of Finnish water gauge stations in 1970 [19]

1	2	3	4	5
The water gauge	Reference level [cm]	The change of mean water on 10 years [cm]	Theoretical mean water [cm]	Annual mean water level [cm]
Kemi	NN – 204.7 = N60 – 167.5	–7.3 ± 0.0	R + 166.8	162.6
Vaasa	NN – 203.1 = N60 – 166.7	–8.0 ± 0.7	R + 161.5	160.6
Mäntyluoto	NN – 201.1 = N60 – 171.5	–0.4 ± 0.4	R + 168.3	166.2
Degerby	P1 – 432.2	–4.6 ± 0.3	R + 177.1	–
Hanko	NN – 193.7 = N 60 –186.1	–3.1 ± 0.3	R + 184.5	184.2
Helsinki	NN – 194.4 = N60 – 189.4	–2.5 ± 0.3	R + 187.5	187.0
Hamina	NN – 194.0 = N60 – 188.6	–2.2 ± 0.7	R + 189.4	188.8

Table 5. Values of theoretical mean water (MW) [mm], approved by the Finnish Meteorological Institute for the years 2013–2014 [18]

The water gauge	MW 2013 [mm]				MW 2014 [mm]			
	NN	N43	N60	N2000	NN	N43	N60	N2000
Kemi	–646	–416	–274	137	–652	–422	–280	131
Vaasa	–689	–452	–325	109	–693	–456	–329	105
Mäntyluoto	–537	–377	–241	143	–540	–380	–244	140
Degerby	–325	–234	–150	123	–326	–235	–151	122
Hanko	–153	–126	–77	175	–152	–125	–76	176
Helsinki	–104	–104	–54	198	–103	–103	–53	199
Hamina	–66	–75	–12	200	–65	–74	–11	201

Presently Finland has four systems of geodesic levelling: NN, N43, N60, N2000.

The first highly-precise leveling in Finland was performed in the years 1892–1910. The Finnish height system NN (*Normaali Nolla*) was the result of that levelling. The datum for the Finnish NN was defined as the datum point of the water gauge located in Katajanokka, Helsinki. This is 30.465 meters below the main reference point of Finland, located near the Astronomical Observatory in Helsinki.

The second highly-precise leveling in Finland was performed in 1935–1975. Initially the height system N43 was defined on the basis of measurements from 1935–1955, then the system N60 was defined on the basis of two above mentioned levelings.

The height system N2000 is based on the third precise leveling in Finland carried out in 1978–2006. This system is the Finnish realization of the joint European Height System and its reference level is derived from the NAP. Heights in N2000 differ by 13–43 cm from the height of the previous national Finnish height system N60. Most differences are due to land uplift calculated for the year 2000 [18].

In this study we have obtained maximum and minimum yearly sea levels for Finnish water gauge stations from the period 1945–2010 in the N2000 system. The observation series of hourly sea levels are obtained from Finnish hydrological annuals in the Finnish NN system. The other part of hourly sea levels from 1971–2010 has been obtained from the Finnish Meteorological Institute. These data have already been converted in reference to theoretical mean water. In further analyses applied in this study for all Finnish data the reference level was the level of theoretical mean water for a given year.

Conversion of water level from annual data of Finnish stations from the NN system to the level referred to the theoretical mean water

In Finnish hydrological annuals Vedenkorkeusarvoja [19], apart from hourly data on sea levels you can find information including measurement characteristics of each water gauge station, contained in table 4.

To convert the sea level from the NN system to a level referred to the theoretical mean water we should subtract from the measured sea level found in the annual the value of reference level (Table 4, column 2), then subtract the value of theoretical mean water for a given year at a given station (tabular data from FMI, Table 5).

Example

The water level in the NN system measured on the mareograph at Kemi in 2013 is 100 cm.

We subtract from that value the reference level of the mareograph, that is 204.7 cm (Table 4, column 2):

100 cm – 204.7 cm = –104.7 cm +
– NN level in respect to the mareograph datum.

Then, we subtract the theoretical mean level for Kemi in 2013, that is –646 mm, from the obtained value (Table 5):

–104.7 cm – (–64.6 cm) = –40.1 cm +
– sea level relative to theoretical mean level.

Estonia

On the eastern coast of the Baltic sea (Russia, Estonia, Latvia, Lithuania, Poland) the Baltic Height System (BHS) was used as early as in the 1950s. The system is based on long-term observations of mean sea level at the Kronstadt gauge in 1825–1840 (Gulf of Finland). This height system was updated in 1977 and called the Baltic Height System 77 (BHS 77). The system is also known as East European United Precise Leveling Network (UPLN) [20, 21].

Estonia presently uses the height system BHS-77, whose reference base is connected with the datum (null point) of the Kronstadt gauge (Russia). This datum is set on the Kronstadt gauge at a height +500 cm. As a result of global increase of the sea level the Kronstadt datum at present does not correspond to the mean sea level of that gauge [20, 22]. In spite of this, mean sea level on gauges in Estonia oscillates around the Kronstadt datum. The null points of Estonian gauges are at least once a year checked in respect to local datum points (benchmarks) [23].

The year 1996 marked a renewal of precise leveling network on the basis of 120 GPS points [24, 25]. At the end of 2011 Estonia in cooperation with Latvia completed measurements, which constituted their contribution within the European Combined Geodetic Network. The datum for that network is NAP [26].

For this study we have acquired hourly series of sea level values and maximum, mean and minimum yearly values from the Estonian Meteorological Institute (*Eesti Meteoroloogia Ja Hüdroloogia Instituut*) from the water gauges in Narva-Jõesuu, Pärnu, Ristna, Tallinn. The received data were referenced to the Kronstadt gauge datum, that is +500 cm. To make these data comparable with data from other Baltic states, the observation series were lowered by 500 cm, then brought to one ordinate of NAP datum using transformations of national reference systems to standards of the European Vertical Reference System [10]. Detailed conversions are given in table 6.

Table 6. Corrections of conversions from BHS 77 (Kronstadt) system to EVRS 2000 (NAP)

The water gauge	Geographical coordinates	Correction from the system BHS 77 to the system EVRS 2000 (NAP) [cm]
Narva (1951–2010)	59.46666 N, 28.03333 E	13.0 (13.0)*
Pärnu (1951–2010)	58.36666 N, 24.50000 E	13.4 (13.0)
Ristna (1962–2010)	58.91666 N, 22.06666 E	12.6 (13.0)
Tallinn (1954–1994)	59.44943 N, 24.77555 E	12.6 (13.0)

* The correction in parentheses after rounding

Lithuania

The first leveling network in the territory of today's Lithuania was formed in 1865–1870 in Eastern Prussia. It connected gauge stations in Gdańsk, Baltijsk and Klaipeda. In 1875 another line of leveling was created as part of the National Geodetic Network of Prussia: Konigsberg – Sovetsk – Mikytai – Klaipeda – Nemirseta. The reference point to that network was reference mark at the astronomical observatory in Berlin at the height of 37.000 m above NAP. In 1930–1940 in the independent Lithuania a national leveling network was adapted from those existing in the neighboring states, Germany and Russia. After World War II in 1948–1950 the Lithuanian leveling network was extended, standardized and fully incorporated into the national network of the USSR. The reference level was that in Kronstadt in 1969. Regulations of the entire network were completed in 1977 (Baltic Height System). The modern leveling network of Lithuania, the Lithuanian National Geodetic Vertical Network (NGVN), is a combination of leveling networks from various periods. In 2000 the network of Lithuania was incorporated into the United European Leveling Network. Although the system used in Lithuania is that based on the Kronstadt datum, this country intends to adopt soon the European Vertical Reference System based on the NAP [27, 28, 29].

For this study the authors have received hourly sea levels for the stations in Klaipeda and Nida from the years 1993–2010 from the Environmental Protection Agency of Lithuania. For the whole hourly observation series of sea level values for each station the value 500 was subtracted to get one ordinate of the gauge (0.00). Then one ordinate of the NAP datum was obtained using transformations to standards of the EVRS 2000 [10].

Details of the conversions are given in table 7.

Table 7. Corrections of the conversions from the system BHS 77 (Kronstadt) to EVRS 2000 (NAP)

The water gauge	Geographical coordinates	Correction from the system BHS 77 to the system EVRS 2000 (NAP) [cm]
Kłajpeda (1993–2010)	55.72971 N, 21.08250 E	+10
Nida (1993–2010)	55.30305 N, 21.01055 E	+10

Poland

First height systems were established in the Polish territory in the 1870s. Leveling on the lands under foreign rule was performed by various instruments and methods with various reference levels adopted. For the territory under Austrian rule the adopted reference level was the mean level of the Adriatic to which the height of nodal point was referred, the datum point of the gauge located on Sartorio pier in Trieste. The height of this datum point was determined to be 3.352 m. Under Prussian rule the earliest reference level in use was the null point of the gauge in Gdańsk – New Port (Neufahrwasser). From 1878 for the whole Prussian network the adopted reference level was that of *Normal-Hohenpunkt* physically marked as a line on a pole of the astronomical observatory in Berlin, marking 37.00 m above the so called *Normal-Null*, that is 37 m above NAP. Under Russian rule, heights of the leveling network from 1871–1893 were referred to the Baltic–Black Sea level, that is a level based on mean levels of the two seas. Many height marks of the Prussian network were later incorporated in measurements of subsequent Polish networks. There are very few points of the former Austrian and Russian networks within today's borders of Poland. Before and after World War II in Poland four leveling campaigns for precise leveling campaigns were realized: I – 1926–1937, II – 1947–1958, III – 1974–1982, IV – 1999–2012.

The final work of the fourth leveling campaign is to be a new vertical reference system in Poland since 1 January 2014 compatible with EVRF2007-NH [30, 31, 32]. The outcomes of those campaigns were as follows:

- in the campaign 1926–1937 the mareograph in Gdynia was related to the reference mareograph in Amsterdam with the corresponding datum point placed on the city hall in Toruń at the height of 50.518 m above NN;
- in the campaign 1947–1958 the main datum point on the Toruń's city hall was equaled with NAP and with the Kronstadt datum point;
- in the campaign 1974–1982 7 mareographs in Świnoujście, Kołobrzeg, Ustka, Łeba, Władysławowo, Hel and Gdańsk-Nowy Port were related to the reference mareograph in Kronstadt;
- in the campaign 1999–2012 23 reference points were defined, and the reference level Kronstadt 86 was adjusted to the new Kronstadt 2006 system.

From the precise leveling and the comparison of the ordinate of that datum point in the Kronstadt system it follows that [34]:

$$H_{Kr} = H_{Toruń}\ NN - 0.084\ m$$

For the purpose of this work the authors have received from the Institute of Meteorology and Water Management (*IMGW*) hourly (obtained every 4 hours) values of sea level for five water gauge stations: Świnoujście, Kołobrzeg, Ustka, Władysławowo and Gdańsk. For the whole observation series the hourly values of sea level, for each station the value 500 was subtracted to obtain one ordinate of the gauge datum (0.00 NN).

Topography of Baltic Sea water surfaces during extreme storms

We have used sea level observation data from the period of 1960–2010 delivered by 33 gauge stations located along the Baltic coast. The data were converted to one reference level, the NAP used in the EVRS system. The conversion allows to present distortions of Baltic water surfaces on a given day and time. The more important effect of these calculations, however, is now possible presentation of a geographic model of the distribution of extreme sea levels in the studied period.

Figure 4 shows a synoptic situation on 1–2 Nov 2006, with a low pressure moving eastward from the North Atlantic through Scandinavia and the Baltic Sea. Due to the presence of that low, water gauges in the western Baltic and Danish Straits on 1 Nov 2006 recorded high water levels (80 cm above NAP) (Fig. 5). On the same day low sea levels were recorded in the Gulf of Finland (0–20 cm) and the Gulf of Bothnia (–20 to –60 cm below NAP). The Baltic surface characteristics changed over just one night. High sea levels moved to Polish and eastern coasts of the Baltic. An outstanding change occurred on 2 Nov 2006 in the Gulf of Finland (+60 cm above NAP) (Fig. 5). Such presentation of Baltic Sea level variations in a standardized height system EVRS is essential for forecasts and modeling of future storm surges.

The significant outcome of data conversion to base them on one reference level is the presentation

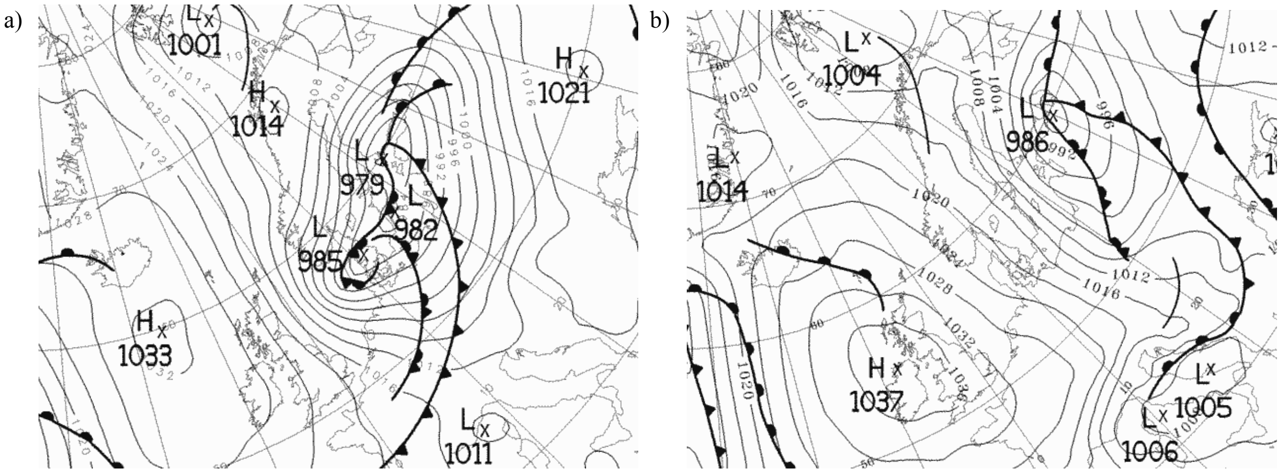

Fig. 4. A synopsis in Europe and North Atlantic on 1 Nov 2006 (a) and 2 Nov 2006 (b) [33]

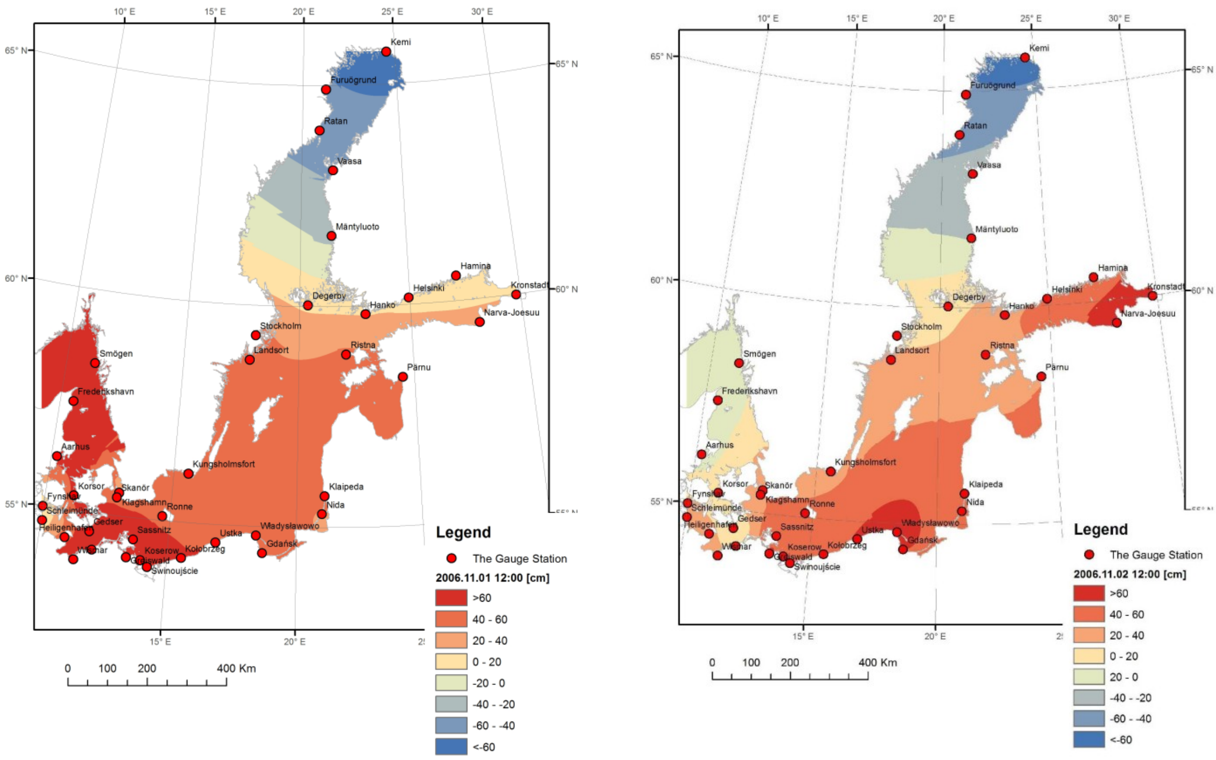

Fig. 5. The Baltic surface on 1 and 2 November 2006, 12.00 UTC

of extreme Baltic Sea levels. The analysis has yielded a geographical distribution of maximum and minimum sea levels in the years 1960–2010 (Fig. 6a, 6b).

Water gauge stations in the gulfs, quite far from open waters of the Baltic, with relatively shallow depths and subject to more frequent passages of low pressure systems, will experience much greater values of extreme sea levels (Gulf of Riga and Pärnu Bay, Pärnu: +296 cm, –101 cm, Gulf of Finland, Hamina: +197 cm –115 cm, Gulf of Bothnia, Kemi: +209 cm, –123 cm, Bay of Mecklenburg, Wismar: +198 cm, –190 cm) than stations sited directly by open water area of the Baltic (Aland Sea, Degerby: +100 cm, –65 cm, Northern Baltic Proper, Lansort: +95 cm, –70 cm, Southern Baltic Proper, Kungsholmsfort: +110 cm, –89 cm).

The Bay of Mecklenburg is an area with greatest negative storm surges, which is related with relatively shallow depths of the area and the so called bay effect.

The Swedish coast of the Central Baltic (Northern and Southern Baltic Proper, Western Gotland Basin) are least subject to extreme sea levels, mainly due to the eastern exposition of that coast, that is the direction opposite to that of low pressure system movement.

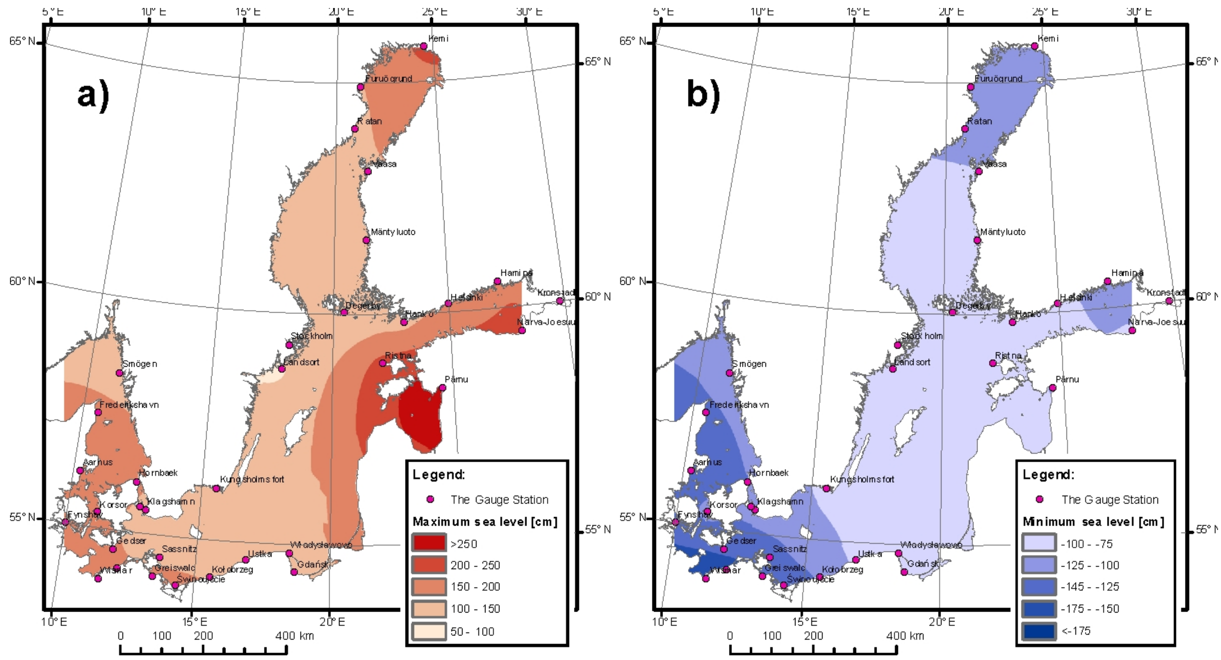

Fig. 6. Geographical distribution of maximum (a) and minimum (b) sea levels in the period 1960–2010

Summary and conclusions

At present geodetics services of Baltic states have recognized the Normaal Amsterdams Peil or NAP as the reference level in their geodetic networks and have agreed to adopt one joint European Vertical Reference System. NAP is established on the basis of mean sea levels in Amsterdam, well documented sea level observations in the Dutch major port and repeatedly verified precise leveling networks of an increasingly higher accuracy, originating in the early 1800s. All earlier and present sea level observations in individual countries can be converted to the reference level EVRS realized by the NAP. We can now demonstrate distortions of Baltic sea surfaces in time and space.

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