

Small Publications in Historical Geophysics

No. 8

**Computation of Historical Shore Levels in Fennoscandia
due to Postglacial Rebound**

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Summer Institute for Historical Geophysics
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Contents

1. Background
 2. Postglacial uplift rates
 3. Rate of global sea level rise
 4. The impact of height systems
 5. Calculation of the height of a historical shore level
 6. Calculation of the year of a historical shore level
 7. On the error limits
 8. Final comments
- References

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1. Background

As is well known, postglacial rebound causes the shore-line in Fennoscandia to fall continuously relative to the land. Consequently, in earlier days shore-lines were situated on higher levels and more inland. This is a fundamental phenomenon when studying the historical development of coastal regions in the Baltic Sea area. Typical examples could be studies of, say, a 17th century fishing harbour now abandoned, a 15th century coastal town no longer in contact with the sea, or an ancient Viking ship route nowadays on dry land.

With knowledge of present rates of postglacial uplift it is possible to make simple computations of historical shore levels dating back in time to the Viking Age. This publication includes recent geophysical development allowing an improved computation of such historical shore levels, of potential interest to geographers, historians and archeologists. Moreover, it includes a simple method to estimate the uncertainty of the result, something that has hitherto often been neglected.

2. Postglacial uplift rates

A consistent and accurate set of postglacial uplift rates along the coasts of Fennoscandia has been published by Ekman (1996). These uplift rates are primarily computed for a large number of sea level stations (mareographs), where sea level has been recorded; see Table 1. The uplift rate is in principle computed by linear regression of the time series of annual means of the sea level at each station. Special care was taken to select only reliable stations with sufficiently long sea level records; many of them have records of about 100 years.

The sea level records originally covered different time periods. In order to be comparable with each other, however, all uplift rates must refer to a common standard time period, a fact noted already by Blomqvist & Renqvist (1914). This is important in order to eliminate sea level changes due to climatic changes between different time periods. The standard period for the uplift rates of Table 1 is the 100-year-period 1892 - 1991. Any sea level station not containing these years was reduced to the standard period by comparison with a reference station containing all years. The main reference station used was Stockholm, since it is situated close to the middle of the Baltic Sea and has the longest record, covering the years of all the other stations. In this way Table 1 contains a consistent set of uplift rates, the maximum rate being 8.8 mm/yr.

Table 1. Postglacial land uplift rates (U) relative to sea level for the 100-year-period 1892 - 1991 (mm/yr). The stations are in anti-clock-wise order around the Baltic and grouped by countries. Only stations with $U > 0$ mm/yr are included; for a complete list see Ekman (1996).

Mareograph	Lat.	Long.	U
Kronstadt	59 59	29 47	0.09
Hamina	60 34	27 11	1.67
Helsinki	60 09	24 58	2.28
Hanko	59 49	22 58	2.99
Turku	60 25	22 06	4.05
Degerby (Åland)	60 02	20 23	4.11
Lemström (Åland)	60 06	20 01	4.57
Lypyrtti	60 36	21 14	5.06
Rauma	61 08	21 29	5.22
Mäntyluoto	61 36	21 29	6.31
Kaskinen	62 23	21 13	7.11
Vaasa	63 06	21 34	7.62
Pietarsaari	63 42	22 42	8.04
Raahe	64 42	24 30	7.54
Oulu	65 02	25 26	6.66
Kemi	65 44	24 33	7.14
Furuögrund	64 55	21 14	8.75
Ratan	64 00	20 55	8.16
Draghällan	62 20	17 28	7.57
Gävle	60 41	17 10	5.90
Björn	60 38	17 58	5.95
Stockholm	59 19	18 05	3.98
Grönskär	59 16	19 02	3.97
Södertälje	59 12	17 38	3.66
Landsort	58 45	17 52	3.06
Visby (Gotland)	57 39	18 18	1.45
Ölands norra udde	57 22	17 06	1.29
Kungsholmsfort	56 06	15 35	0.20
Varberg	57 06	12 13	0.77
Smögen	58 22	11 13	1.99

Table 1, continued: Postglacial land uplift rates relative to sea level for the period 1892 - 1991 (mm/yr).

Mareograph	Lat.	Long.	<i>U</i>
Frederikshavn	57 26	10 34	0.49
Hirtshals	57 36	09 57	0.38
Oslo	59 54	10 45	4.10
Nevlunghavn	58 58	09 53	1.56
Bergen	60 24	05 18	0.24
Heimsjø	63 26	09 04	1.47
Narvik	68 26	17 25	3.06
Vardø	70 20	31 06	0.81

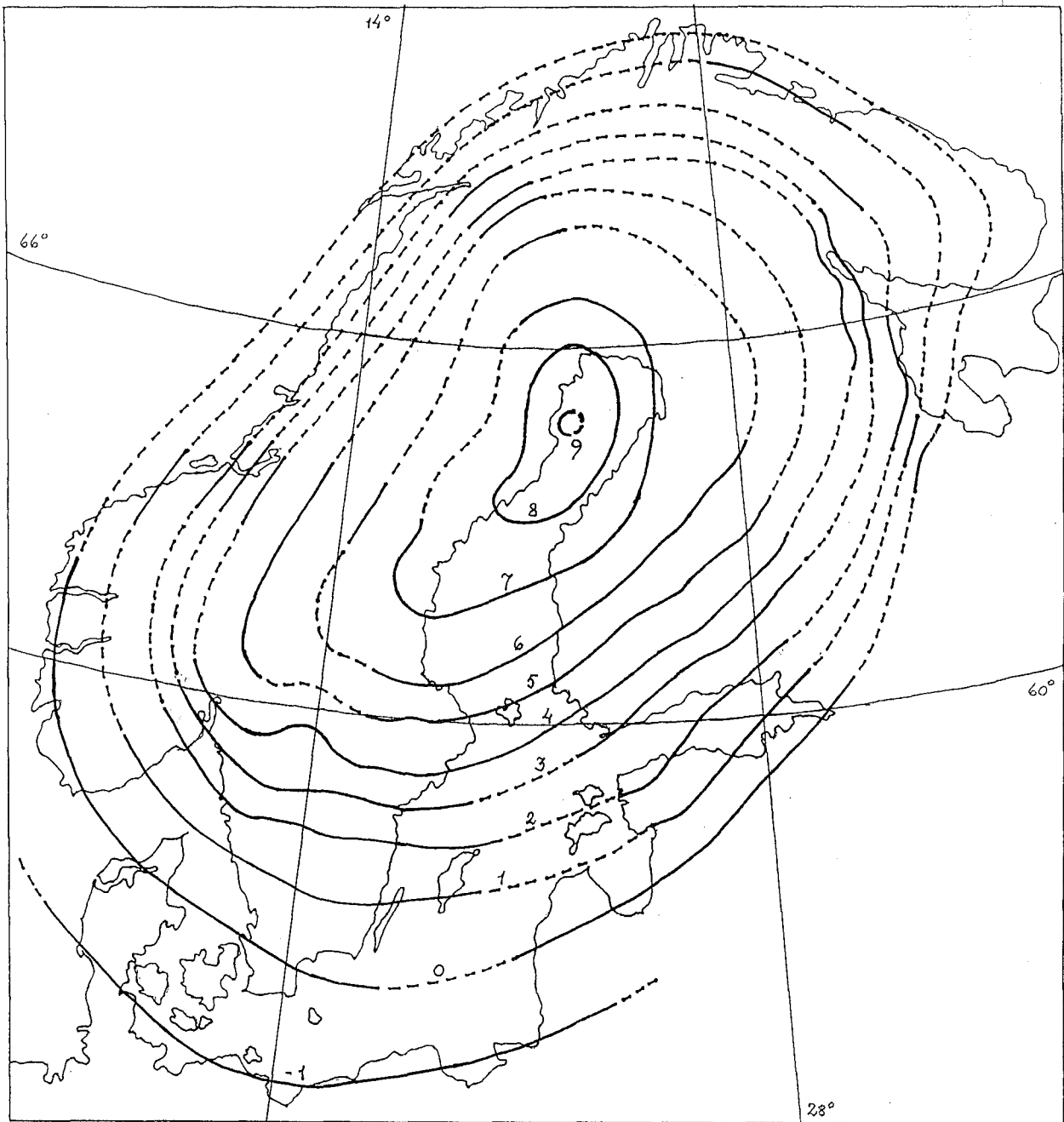


Figure 1. Postglacial uplift of Fennoscandia relative to sea level 1892 - 1991 (mm/yr). From Ekman (1996).

Based on these uplift rates of the sea level stations, together with inland data of lower weight from repeated levellings and a few lake level stations, a consistent map of the postglacial uplift of Fennoscandia was constructed; see Figure 1. The map thus shows the land uplift relative to sea level for the time period 1892 - 1991. Further details may be found in Ekman (1996). The uplift rates range from 9 mm/yr in the northern part of the Gulf of Bothnia to - 1 mm/yr at the southern coast of the Baltic proper. The geographical pattern of the uplift rates predominantly reflects the distribution of ice thickness during the Ice Age.

3. Rate of global sea level rise

The map in Figure 1 shows the land uplift relative to sea level (apparent land uplift). However, sea level itself is known to rise, too, at least for the time being. This is so because of the presently mild climate, which causes glaciers to melt, increasing the amount of sea water, and sea water to expand thermally.

The rate of this global sea level rise is not easy to determine but seems to be close to 1 mm/yr. There might be some regional differences in this value. Recently, however, an accurate determination of the sea level rise in the Baltic Sea area was made by Lambeck et al (1998); the result is 1.0 mm/yr. This determination made use of a geophysical model of theirs of the Fennoscandian postglacial rebound, based on geological shore-line data and refined by mareograph data. The model may be said to predict present uplift rates that do not include the present global sea level rise. When compared to the uplift rates of Table 1 that do include the sea level rise, the latter could be determined. This means that the obtained value of 1.0 mm/yr refers to the same time period as that for the land uplift rates in Section 2. The value is in agreement with early estimates by Mörner (1973) and Lisitzin (1974).

However, the sea level rise is a phenomenon that has changed with time. This can be clearly seen in the world's longest sea level record, that of Stockholm, commencing 1774. Analysing this record, Ekman (1988, 2000) found an apparent uplift rate that was 1.0 mm/yr larger during the earlier half of the time period than during the later half. This change was found to be statistically highly significant; it reflects the added sea level rise since around 1890, the end of the "Little Ice Age". Similar effects have been found in the three other very long records of the world, namely Amsterdam, Brest and Liverpool (Woodworth, 1990, 1999), of which Amsterdam started already in 1700 (but was later on discontinued).

What has been said above implies that before about 1890 the sea level rise was close to zero. This is in good accordance with the sparse knowledge we

have from the stability of glaciers at that time. Adding the nowadays fairly good knowledge we have of the global temperature during the last 1000 years or since perhaps 800 A.D. (Hammer et al, 1980; Mann et al, 1999), we may state that the sea level rise must have been close to zero during most of the last millenium. Further details may be found in Ekman (2000). This means that apparent uplift rates before 1890 are in general 1.0 mm/yr larger than their values given in Section 2, at least as a long time average.

4. The impact of height systems

A few things should be said also about height systems involved in computations of historical shore levels.

First, to handle the postglacial uplift, heights in a height system normally refer to a certain year, sometimes called the epoch of the height system. The official Swedish height system RH 70 refers to the year 1970, while the official Finnish height system N 60 refers to the year 1960 (see e.g. Mäkinen, 1987). In Norway the situation is a little more unclear, but in the only coastal area with considerable uplift (the Oslo area) the Norwegian height system NN 1954 is in our context valid for approximately 1950. Thus the years mentioned should be used as the starting years for any shore level calculation related to these height systems.

Second, the zero level of a height system does not exactly coincide with the mean sea level. This is due to the sea water having different salinity and thereby different density in different parts of the sea etc. Thus even the shore level (mean sea level) of the defining year of the height system might have a height that differs from zero. For the Swedish height system RH 70 mean sea level (1970) in the northernmost part of the Gulf of Bothnia reaches a height of 0.2 m (cf. Ekman & Mäkinen, 1996); otherwise the effect is small.

5. Calculation of the height of a historical shore level

Let us denote the postglacial uplift rate of Table 1 and Figure 1 by U , the defining year (epoch) of the applied height system by t_0 , the year of a historical shore level by t , and the height of the same historical shore level by H . Also, let H_0 be the height of the shore level at the year t_0 (i.e. the discrepancy between mean sea level and the zero level of the height system). Then we may write

$$H = H_0 + U(t_0 - 1890) + (U + 1.0)(1890 - t) \quad (1)$$

By inserting a year t , the height H of the historical shore level can be easily calculated. We note that inclusion of the sea level rise of 1.0 mm/yr is

important; otherwise we would make an error of as much as 1 m in the height of a Viking Age shore level.

By two small approximations the above expression may be simplified to

$$H = (U + 1.0)(t_0 - t) \quad (2)$$

Here the small quantity H_0 has been omitted, and U for the short time period between 1890 and t_0 has been replaced by $U + 1.0$. The effects of these two approximations happen to more or less cancel each other. The error does in practise not exceed 0.1 m. Nevertheless, it is important to remember that, strictly speaking, the original version (1) is the correct one. In some yet unknown future height system the two effects might add up instead of cancel out, and then would have to be taken into account.

In any case one must bear in mind that (1) or (2) should not be used further back in time than to about 1000 or 800 A.D. For older times one should rely on models based on geological shore-lines. The reason for this is twofold: the exponential character of the uplift and the insufficient knowledge of ancient climate.

The rates U and 1.0 contain uncertainties that will propagate through (1) or (2) to the resultant value of H . The uncertainty of U , more specifically its standard deviation, has been determined within the land uplift computations from the sea level data. It amounts to about 0.20 mm/yr at most sea level stations; for a coastal point in between it should be somewhat larger. Let us put it generally at 0.25 mm/yr. This value can be used for U as well as $U + 1.0$ back to maximum 1700, which is as long as we have support from sea level data. Before 1700 we have to rely on the climatically based conclusions regarding the sea level behaviour. For that time period, therefore, we have to increase the estimated standard deviation to 0.35 mm/yr, as explained in Section 7. Denoting the standard deviation of H by s_H we may consequently write $s_H = 0.25(t_0 - 1700) + 0.35(1700 - t)$.

From mathematical statistics it is well known that twice the standard deviation, i.e. $2s_H$, is very close to a 95 % confidence limit. Thus $\pm 2s_H$ may be said to represent the error limits of the height of the shore level:

$$2s_H = 0.5(t_0 - 1700) + 0.7(1700 - t) \quad (3)$$

Inserting the year t for the historical shore level, the error limits of its height can thus be estimated.

As an example we make a shore level calculation for the Viking Age town of Birka west of Stockholm. Here jetties dated to around 950 A.D. have been found at the approximate height 5.5 m in the Swedish height system RH 70 (Ambrosiani, 1982). The present apparent land uplift rate according to Section 2 is 4.1 mm/yr. Putting $t = 950$, $t_0 = 1970$ and $U = 4.1$ mm/yr into (2) we obtain $H = 5.2$ m. (The same result is obtained from (1) with $H_0 = 0.1$ m.) Furthermore, putting the mentioned values of t and t_0 into (3) we obtain $2s_H = 0.7$ m. Thus we find a shore level height at 950 A.D. of 5.2 ± 0.7 m. The observed height of jetties of about 5.5 m is in good agreement with this and falls well within the error limits.

6. Calculation of the year of a historical shore level

If we instead prescribe a certain height of a shore level we can easily date the shore level by solving the simplified equation (2) for the year t ,

$$t = t_0 - \frac{H}{U + 1.0} \quad (4)$$

or, if necessary, do the same thing with the original equation (1). A common problem of this kind is to determine when the 5-meter-curve on a topographic map was a shore-line.

The error limits (95 % confidence limits) of the dating can be estimated in a somewhat similar manner as with the height. Denoting the standard deviation of t by s_t we may write approximately $s_t = s_H/(U + 1.0)$, i.e.

$$2s_t = \frac{0.5(t_0 - 1700) + 0.7(1700 - t)}{U + 1.0} \quad (5)$$

As an example let us date the 5-meter-curve at Luleå, a coastal town close to the land uplift maximum at the Swedish coast of the Gulf of Bothnia, with its medieval church nowadays quite far inland. The present apparent land uplift rate according to Section 2 is 8.4 mm/yr. Putting $H = 5.0$ m, $t_0 = 1970$ and $U = 8.4$ mm/yr into (4) we obtain $t = 1440$. Furthermore, putting the mentioned values of t , t_0 and U into (5) we obtain $2s_t = 35$, which we prefer to increase to 40 because of the distance to mareographs. Thus we find the 5-meter-curve to be the shore-line at the year 1440 ± 40 . This curve will give a good picture of the excellent possibilities to go by boat to the newly erected church and its surrounding market-town at that time.

7. On the error limits

The error limits (3) and (5) rely on the estimated confidence limits 0.5 and 0.7 mm/yr, valid after and before 1700, respectively. The first of these values is quite well determined from mareograph analyses (although it might be 0.4 very close to a mareograph and 0.6 farther away from one). The second value is more debatable and needs some explanation. The average climatic sea level rise during the last millenium (up to about 1890) was estimated in Section 3 at 0.0 mm/yr. From climatic considerations it seems very unlikely that this figure could be in error by more than ± 0.5 mm/yr (although the sea level rise during a single century might have deviated from zero somewhat more than that). We may here interpret this as a 95 % confidence interval. Hence the total confidence limit from both the observed land uplift and the estimated zero average sea level rise becomes $[(0.5)^2 + (0.5)^2]^{1/2} = 0.7$ mm/yr (to be used before 1700 when there are no sea level data).

It should be noted that by shore level in this publication is meant the long-term mean shore level at the year in question. In a shorter time perspective things can be somewhat different. Due to mainly the wind conditions over the Baltic entrance there is sometimes a quite considerable seasonal variation in the Baltic sea level, especially in the central and northern parts of the Baltic Sea. The average sea level during one month could here be 0.5 m above or below "normal", i.e. above or below the long term mean sea level, particularly in early spring (Ekman, 1996a). This implies that foundations of old constructions might sometimes be found down to half a meter below the shore level as calculated according to Section 5.

8. Final comments

The mentioned effect of considerable seasonal low waters might apply to the foundations of the old city walls and the old Royal Palace in Stockholm. These buildings, together with some other historical remains, have been used to claim an apparent land uplift varying considerably with time during the last millenium; see Ambrosiani (1982), Åse (1984), Mörner (1984), Miller (1986) and others. In particular, the papers claim that the apparent land uplift at Stockholm between approximately 1500 and 1700 was close to zero. However, this would imply a climatic sea level rise of nearly 5 mm/yr during these centuries to counterbalance the uplift of the crust. This has to be ruled out according to present knowledge of climate at that time; cf. Section 3. Nor is there any known regional oceanographic phenomenon that could produce such a large sea level change (cf. Ekman, 2000). Changes in the gravity field due to mass flow in the mantle or the core would produce changes in the geoid and, thereby, in sea level, but also these effects will be too small (cf. Ekman &

Mäkinen, 1996a). A critical discussion of the interpretation of some of the historical remains has been given by Nyberg (1986). In addition, the old observations by Celsius of the seal rock at Iggön in the Gulf of Bothnia contradicts any substantial sea level rise between about 1563 and 1731 (Ekman, 1991).

Another point that needs to be mentioned is the effect of the non-linear, i.e. exponential, character of the uplift as we go back enough in time (see e.g. Lambeck et al, 1998a). This effect could reach the order of decimeters 1000 years ago; its true value is dependent on the still somewhat uncertain viscosity structure in the Earth. However, there are indications of climate changes (Hammer et al, 1980) yielding a sea level rise during the first centuries of the past millenium. This should partly compensate the exponential effect in our time perspective.

Altogether, the simple method described in this publication for computing old shore levels seems to be realistic enough for historical purposes.

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