Small Publications in Historical Geophysics

No. 31

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Martin Ekman

Summer Institute for Historical Geophysics
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1. Introduction

Postglacial rebound plays a fundamental role in understanding the archaeology and history of the Nordic and Baltic area. Considerable land areas have gradually risen, and are still rising, from the sea, causing continuously changing living conditions for people along the coasts.

The importance for history of this phenomenon was first realized by Celsius (1743). He succeeded in making the first rough determination of the rate of the land uplift (using data from an abandoned seal rock), although he himself considered it to be a water decrease. Making a linear extrapolation of this rate he tried to estimate historical and future levels of the sea relative to the land. Later on knowledge and understanding of the phenomenon increased, allowing a better calculation of historical shore levels.

We will here limit ourselves to the last 1500 years, for which present uplift rates, correctly handled, can be used as a starting point. A simple way of calculating shore levels back to the Viking Age, including their uncertainty, was given by the author several years ago (Ekman, 1996a, 2001). This method is here extended and updated; the present publication gives an improved way of calculating historical shore levels, including their uncertainty, valid back to about 500 A.D., with special application to the central Baltic Sea area.

The main reason for extending the time period beyond the Viking Age back to about 500 A.D. is the recent insight that a drastic change of living conditions and settlements occurred in the middle of that century. A cluster of extreme volcanic eruptions in the years 536, 540 and 547 A.D. in various places on the Earth caused very cold summers globally for a whole decade with long-lasting consequences, in the Nordic area preventing normal agriculture; see Gräslund (2008) and Büntgen et al (2016). This caused famine among the population, changed the distribution of power among the survivors, and made inland people move to islands and archipelagos.

The whole society thus underwent a considerable change around and after 550 A.D. In the central Baltic Sea area the climate crisis made people move in large numbers to the Åland Islands, seeking a living by seal-hunting and sea fishing instead; see Ilves (2017). The Åland Islands at that time became more densely populated than the Mälaren region in eastern Sweden, also leading to a first organization of society into villages. (Also, the Nordic speciality of clinker-built boats was developed during this time.) This makes it interesting to calculate the shore level at that time as accurately as possible, in order to be able to relate it to archaeological traces of coastal activities and the foundation of coastal settlements as well as to the location of grave fields from that time.

The method given here to calculate a historical shore level is based on present uplift rates; these are then combined with knowledge of the climatic sea level rise, the non-linearity of the uplift process, and the non-zero height of mean sea level in the height system. There are nowadays two different possibilities to apply present uplift rates for this purpose: uplift rates from continuous sea level recordings and uplift rates from continuous satellite positioning. In both the sea level approach and the satellite approach the climatic sea level rise has to be dealt with, but in different ways for the two approaches. Furthermore, when going more than 1000 years back in time it is necessary to take into account that the uplift process in the long run is not linear but exponential. In addition, the small discrepancy between mean sea level and the zero level of the height system needs to be handled. We will treat these items in the order they are mentioned here, and then combine them into a simple method for calculating historical shore levels, including an estimate of their uncertainty. Finally we will apply this method to determine the shore level at the climate crisis around 550 A.D. in the central Baltic Sea area.

2. Postglacial uplift rates

As mentioned, there are nowadays two different approaches when dealing with the rate of the ongoing postglacial rebound (glacial isostatic adjustment). It could be done either using data from sea level recordings or using data from satellite positioning.

We start with the sea level approach. A consistent and accurate set of postglacial uplift rates along the coasts of Fennoscandia, especially in the Baltic Sea, was published by Ekman (1996, 2009). These uplift rates are computed for a large number of sea level stations (mareographs), in principle 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 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. This is important in order to eliminate sea level changes due to climate changes between different time periods. The standard period for the uplift rates is the 100-year-period 1892 – 1991. Any sea level station not containing these years was reduced to the standard time period by comparison with a reference station containing all years. The main reference station used was Stockholm, being situated in the middle of the Baltic Sea and having the longest record, covering the years of all the other stations. The result is a consistent set of uplift rates U_a, spanning from a maximum of

$$U_a \text{ (max)} = 9 \text{ mm/yr}$$

in the northern parts of the Gulf of Bothnia to U_a = - 1 mm/yr at the southern coast of the Baltic proper (the index will be explained below). Based on these rates together with some inland data also a map of the uplift was constructed; the inland parts of this map, however, are now obsolete. A new map with improved inland parts was published by Ågren & Svensson (2007), but also this map is now obsolete. The uplift rates at the sea level stations, on the other hand, are still useful. This is especially the case in the historically interesting central Baltic Sea area, involving the eastern Mälaren region and the Åland Islands, since it contains a comparatively dense net of long-term sea level stations.

We now turn to the satellite approach. A set of consistent and accurate uplift rates of Fennoscandia was recently published by Vestøl et al (2016). These rates, forming a grid and a map over the uplift area, are primarily based on satellite positioning. The uplift rate for each satellite station (permanent reference station for GPS) is in principle computed by linear regression of the vertical position recorded continuously during some 10 years or more; see Kierulf et al (2014). In contrast to sea level observations such a short time period is enough to obtain a sufficiently accurate value. Neither is the value dependent on which time period has been used.

On the other hand, the uplift rates obtained from satellite positioning are not of the same kind as those obtained from sea level recordings. The sea-level-based uplift rates used above reflect the uplift of the crust relative to the sea level, known as the apparent uplift in geophysics/geodesy and the shore displacement in history/archaeology. The satellite-based uplift rates reflect the uplift relative to the centre of mass of the Earth (or the reference ellipsoid), known as the absolute uplift. There are two differences involved here; see e.g. Ekman (2009).

One difference is due to the postglacial uplift itself. The uplift process of the crust is connected to a viscous inflow of mantle below the crust (lithosphere). The mass thus added causes an increase in gravity. This, in its turn, causes a rise in sea level, approximately proportional to the uplift itself, with a maximum of 0.6 mm/yr. This gravitational sea level rise, however, can be accurately taken into account. Doing so, one obtains the uplift U_c of the crust relative to a theoretical sea level (the geoid), a sea level not affected by climate. This kind of uplift, here called the climate-free uplift, based on satellite observations, yields uplift rates spanning from a maximum of

U_c (max) = 10 mm/yr

in the Gulf of Bothnia to U_c = 0 mm/yr in the south. (This is what also has been called the levelled uplift.)

The other difference, which is the main one and the one forming the difference between U_c and U_a, is due to the climate. During the last century climate has been comparatively mild, causing glaciers to melt and sea water to expand. This causes a climatic rise in sea level, in this case approximately constant within the uplift area, but in the long run changing with time; see further next section. This effect makes the sea-level-based uplift U_a, i.e. the apparent uplift, somewhat smaller than the satellite-based uplift U_c, i.e. the climate-free uplift. This has to be taken into account when using uplift rates from satellites for calculating historical shore levels. And the change with time of the climate effect also has to be taken into account when using uplift rates from sea level stations for the same purpose.

It should be noted that, apart from the difference due to the climatic effect, treated below, the uplift rates U_a and U_c in an overall perspective agree well with respect to their uncertainties. The uncertainty (standard error) amounts to 0.2 mm/yr for the rates U_a based on sea level stations and about the same for the rates U_c based on satellite positioning; see further Section 7.

3. Climatic sea level rise

The ongoing climatic sea level rise started towards the end of the 1800s. Its rate during the last century, as a global average, is known to be between 1 and 2 mm/yr. There are, however, regional differences. Furthermore, in a wider time perspective the rate depends on the time period studied.

For the Baltic Sea there have been applied two different methods to estimate the climatic sea level rise during the last century. One method is based on comparing postglacial uplift rates from geophysical models with observed uplift rates from sea level stations. The other method is based on comparing uplift rates from satellite positioning with uplift rates from sea level stations.

The first of the two methods to determine the sea level rise was used by Lambeck et al (1998). This determination made use of a geophysical model of theirs of the postglacial rebound, based on geological shore-line data and refined by mareograph data. The geophysical model may be said to predict present uplift rates U_c that do not include the present climatic sea level rise. When compared with the uplift rates U_a of Ekman (1996) that do include the sea level rise, the sea level rise could be determined, thus referring to the same time period as for the uplift rates U_a. Their result was

$$\Delta U = 1.05 \pm 0.25 \text{ mm/yr}$$

The second of the two methods has recently been used by Vestøl et al (2016). In this case use was made of the uplift obtained from satellite positioning, yielding uplift rates U_c of the same kind as a geophysical model, i.e. uplift rates that do not include the present climatic sea level rise. When, as above, compared with the uplift rates U_a that do include the sea level rise, the latter could again be determined, still referring to the same time period. Their result was

$$\Delta U = 1.29 \pm 0.27 \text{ mm/yr}$$

Comparing the two results we note that they agree well within their uncertainties. Hence we here adopt their mean value for further use:

$$\Delta U = 1.2 \text{ mm/yr}$$

As mentioned, however, climatic 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. Analyzing this record, Ekman (1988, 2009) found an apparent uplift rate that was 1.01 ± 0.30 mm/yr larger during the earlier half of the time period than during the latter half. This change reflects the added sea level rise since around 1890. Similar effects have been found in the few other very long records of the world, particularly Amsterdam (Woodworth, 1990; Pugh & Woodworth, 2014) which started already in 1700 (but was later on discontinued).

This implies that before around 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 (Warrick & Oerlemans, 1990). To this we may add the knowledge we now have of the global sea level behaviour from a number of palaeo-environmental records during the last millennia; see Lambeck et al (2010), Church & Clarke (2013) and Lambeck et al (2014). The overall conclusion from all these investigations is that the sea level rise must have been close to zero during most of the last 1500 years.

This means that apparent uplift rates before about 1890 are in general ΔU = 1.2 mm/yr larger than their values according to U_a, at least as a long time average. Moreover, it means that apparent uplift rates before about 1890 are approximately equal to the climate-free rates according to U_c, although after about 1890 they are approximately ΔU = 1.2 mm/yr smaller than those.

4. Exponential effect

When going back in time sufficiently many years, in practice about 1000 years or more, it becomes necessary to take into account the fact that the uplift process is not linear but an exponentially decaying one. The process follows an exponential function governed by the viscosity of the material in the Earth's mantle (see e.g. Ekman, 2009). This material is gradually flowing back beneath the crust, filling, so to speak, the space as the crust is going up. In reality the process is slightly more complicated, since at least two layers in the mantle with different viscosities are involved, the upper mantle and the lower mantle. And to fully model the decaying function one also should take into account the thickness of the crust (lithosphere) and the characteristics of the ice. In our time perspective and for our purpose, however, these latter things do not matter very much; a realistic viscosity of the upper mantle is all that is needed. That is today known with sufficient accuracy from geophysical interpretation of geological shore-line and other data.

Using some realistic value of the viscosity of the upper mantle, or a full geophysical model, like that of Steffen et al (2016), one can compute the effect E of the deviation of the exponential function from a linear one when going back in time. Doing so for the last 1500 years one obtains the following values, back to the year 500, for the central Baltic Sea area (the historical area Uppsala – Mälaren - Åland Islands):

Year	E
2000 – 1500	0.0 m
1500 – 1200	0.1 m
1200 – 1000	0.2 m
1000 – 800	0.3 m
800 – 650	0.4 m
650 – 500	0.5 m

For other areas these figures will have to be modified in proportion to the absolute uplift rate, with a reasonable approximation simply through multiplying by $U_c/6$ (6 mm/yr being the average rate for this area). The figures above constitute an exponential effect to be added to the height of the shore level obtained through a linear calculation according to Sections 2 and 3.

5. Mean sea level effect

A few things should be said also about height systems involved in the calculation, and their relation to mean sea level.

First, heights in a height system normally refer to a certain year, sometimes known as the epoch of the height system. The modern official height systems of the Nordic countries (RH 2000, N 2000 etc.), all connected to the European system EVRS, refer to the year 2000. Thus that year should be used as the starting year 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 temperature and, thereby, different density in different parts of the sea. Thus even the mean sea level (shore level) of the defining year of a height system might have a height H_0 that differs from zero. In the case of the height systems around the Baltic, mean sea level has the following heights, based on Ekman & Mäkinen (1996) transformed to 2000; cf. also Ågren & Svensson (2007):

Sea area	H_0
Gulf of Bothnia	0.2 m
Gulf of Finland	0.2 m
Baltic proper	0.1 m
Kattegat	0.0 m

More specifically, Mälaren and Åland belong to the area with a mean sea level height of 0.2 m. The increasing height towards the inner parts of the Baltic mainly reflects the lower salinity there. These values constitute a mean sea level effect to be added to the height of the shore level obtained through a calculation according to Sections 2, 3, and 4.

6. Calculation of a historical shore level and its uncertainty

We are now prepared to calculate the height H of a historical shore level for any year t back to about 500 A.D.

Sea level approach: Using the apparent uplift rate U_a from sea level recordings according to Section 2, the climatic sea level rise ΔU from Section 3, the exponential effect E from Section 4, and the mean sea level effect H_0 from Section 5, we may write

$$H(t) = U_a(2000 - 1890) + (U_a + \Delta U)(1890 - t) + E(t) + H_0 \qquad (1)$$

Satellite approach: Using instead the climate-free uplift rate U_c from satellite positioning according to Section 2, together with the other quantities, we may write

$$H(t) = (U_c - \Delta U)(2000 - 1890) + U_c(1890 - t) + E(t) + H_0 \qquad (2)$$

Inserting a year t into (1) or (2), the height H of the historical shore level can thus be calculated. The first term in the two formulae represents the uplift relative to sea level during the last century, the second term represents the uplift relative to sea level during earlier centuries, the third term represents the additional uplift due to the exponential effect, and the fourth term represents the additional height due to mean sea level differing from the zero level of the height system.

The formulae (1) or (2) are safely valid back in time to about 500 A.D. Going considerably further back in time we would need more information about the effect of ancient climate, and the exponential decay would be better handled by a direct geophysical model rather than starting from present uplift rates.

The uplift rates U_a or U_c as well as the rate ΔU of the sea level rise contain uncertainties that will propagate through (1) and (2), respectively. The uncertainty of U_a, more specifically its standard error, has been determined within the land uplift computation from the sea level data. It amounts to about 0.20 mm/yr for most sea level stations. The uncertainty of U_c is more difficult to determine, but realistic estimates yield about 0.20 mm/yr for most satellite stations, too. Apart from the difference due to the climate effect, U_a and U_c also agree within their uncertainties. All this taken together, a reasonable uncertainty for the observed uplift rate is 0.2 mm/yr. This value can be used back to maximum 1700, which is as long as we have support from sea level recordings.

Before 1700 we have to rely on more indirect conclusions regarding the sea level behaviour. For that time period, therefore, we have to increase the estimated uncertainty to 0.3 mm/yr. This needs some explanation. The average climatic sea level rise during the last 1500 years (up to about 1890) was estimated in Section 3 at close to zero. From the references there it seems that a reasonable standard error in this average rate would be 0.2 mm/yr (although the sea level rise during a single century might have deviated from zero more than that). Hence the total standard error from both the observed land uplift and the estimated zero sea level rise becomes $[(0.2)^2 + (0.2)^2]^{1/2} = 0.3$ mm/yr, to be used before 1700 when there are no direct sea level data.

Putting the two error estimates above together, we obtain a simple formula for estimating the uncertainty of a historical shore level, valid for both the sea level approach and the satellite approach:

$$s_H(t) = 0.2(2000 - 1700) + 0.3(1700 - t) \qquad (3)$$

Inserting the year t of the historical shore level into (3) thus gives the uncertainty (standard error) of its height. As usual, the error limits (95 % confidence interval) will be twice as large.

7. Applications to the Åland Islands, Gamla Uppsala and Birka

At Gamla Uppsala, north of Mälaren, there are the three imposing burial mounds as well as recently discovered remnants of a very large hall, dated to the late 500s and early 600s; see Ljungkvist & Frölund (2015). These are probably related to the changes in society following after the climatic crisis around 550 explained in the Introduction, with a few survivors becoming more powerful. As also stated in the Introduction, the climatic crisis around 550 caused a large influx of people from these areas to the Åland Islands, where seal-hunting and sea fishing could feed people otherwise starving from failed agriculture. This is shown in the large amount of grave fields all over Åland stemming from that time. There are nearly 11 000 known graves from the period 550 – 1050 compared to a little more than 1 000 for a whole millennium before that; see Ilves (2017). Moreover, at Saltvik (Kvarnbo) on Åland, Ilves (2017) has recently discovered remnants of a large hall, of a similar kind as the one discovered at Gamla Uppsala, and also dated to the same time, i.e. the late 500s and early 600s. The length of the building was no less than 45 m, twice as long as any other contemporary building on Åland. And at Saltvik as at Gamla Uppsala an important church, although smaller, was later erected close to this hall.

Let us, therefore, apply the shore level formulae (1) and (2), including their uncertainty estimate (3), to calculate the shore level at the Saltvik site on Åland coupled to the climate-induced influx of people around and after 550. First the sea level approach: Inserting into (1) and (3) $t = 550$, together with $U_a = 4.8$ mm/yr, $\Delta U = 1.2$ mm/yr, $E = 0.5$ m and $H_0 = 0.2$ m, we find $H = 9.3 \pm 0.4$ m. Then the satellite approach: Inserting into (2) and (3) $t = 550$, together with $U_c = 6.1$ mm/yr and the other quantities unchanged, we find $H = 9.4 \pm 0.4$ m.

The two results agree well with each other, but we should remind ourselves that they are partly connected through the combined estimate of ΔU. As a final value we may adopt a mean of the two, giving the sea level result in this case a somewhat higher weight than the satellite one because of the fairly dense net of long-term sea level stations in the area: $H = 9.3 \pm 0.4$ m. We note that Ilves (2017) finds that the hall is situated at a height of 11 m. This is thus close to the then mean sea level.

Performing the same kind of calculation for the whole of Main Åland we find results spanning from 8.5 ± 0.4 m in the southeast to 9.8 ± 0.4 m in the northwest. These results for the shore level at that time can be used for understanding the location of the new settlements (villages) and their grave fields in relation to the sea.

It is also of interest to calculate the shore level at about 1050, which marks the transition from the Viking Age to the Middle Ages, leading to the erection of churches (Ringbom, 2011) and the organization of society into parishes. For the Saltvik site we find 6.0 ± 0.3 m, and for the whole of Main Åland we find values spanning from 5.5 ± 0.3 m to 6.4 ± 0.3 m. As pointed out earlier, this implies that most of the present Åland medieval churches were originally located close to the sea shore, although this is far from the case today.

Quite recently traces of a somewhat similar hall as the ones at Gamla Uppsala and Saltvik (Kvarnbo) have been discovered at Birka (Korshamn) in the eastern Mälaren area by Kalmring et al (2017), the earliest version of the hall being also in this case dated to the late 500s or early 600s. Performing a calculation according to above for this site we obtain $H = 8.2 \pm 0.4$ m for the shore level at that time. Here the sea level approach and the satellite approach give the same result. This result may be compared with the finding by Kalmring et al (2017) of a harbour construction with land foundations for jetties, indicating a shore level there at that time of about 7.8 m. Thus our calculated value agrees, within its uncertainty, with the observed one, thereby confirming that the method of calculation yields realistic results.

Performing the same calculation for Gamla Uppsala we find there $H = 9.4 \pm 0.4$ m. In this case we have given the sea level approach somewhat lower weight, because of the larger distance of this site to the sea level stations than in the earlier cases. On the whole, for locations not very close to sea level stations the satellite approach alone will work well for our historical purposes.

The heights of the shore levels at 550 as well as 1050 for all three historical sites with halls are summarized in Table 1.

Table 1. Shore levels (H) for the years 550 and 1050 at the historical sites with halls in the central Baltic Sea area. Unit: m. (Height system EVRS epoch 2000 ≈ RH 2000 ≈ N 2000.)

Site	H (550)	H (1050)
Gamla Uppsala	9.4 ± 0.4	6.1 ± 0.3
Saltvik (Kvarnbo)	9.3 ± 0.4	6.0 ± 0.3
Birka (Korshamn)	8.2 ± 0.4	5.3 ± 0.3

Finally a brief remark: An interesting possibility to compare shore level calculations of the kind above with shore level observations may be provided by the observational methods based on phosphate analysis suggested by Ilves & Darmark (2011); see also Ilves (2012) and Mikolajczyk et al (2015).

8. A note on the near future

The principles behind the formulae (1) and (2) can be used not only for looking back into history but equally well for looking forward into the near future. As is well known, the Intergovernmental Panel on Climate Change (IPCC) has, for the present century, predicted various scenarios with rising sea levels due to the ongoing and future climate warming. Introducing a predicted rate of climatic sea level rise ΔU_P we can easily reformulate (1) and (2) to give the height of a future shore level:

$$H(t) = (U_a + \Delta U - \Delta U_P)(t - 2000) + H_0$$

$$H(t) = (U_c - \Delta U_P)(t - 2000) + H_0$$

(Here the quantity E has been neglected as being too small in this time perspective.) Alternatively, introducing instead a predicted total climatic sea level rise ΔH_P we may write

$$H(t) = (U_a + \Delta U)(t - 2000) - \Delta H_P + H_0$$

$$H(t) = U_c(t - 2000) - \Delta H_P + H_0$$

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