Small Publications in Historical Geophysics

No. 24

Postglacial Rebound Modelling during 300 Years based on Fennoscandian Sea Level Data

Martin Ekman

Summer Institute for Historical Geophysics
Åland Islands

2012

Small Publications in Historical Geophysics

No. 24

Postglacial Rebound Modelling during 300 Years based on Fennoscandian Sea Level Data

Martin Ekman

Contents

Summer Institute for Historical Geophysics
Åland Islands

2012

1. Introduction

Postglacial rebound or glacial isostatic adjustment is a geophysical phenomenon that has been studied scientifically for 300 years. However, the phenomenon itself, although not understood, must have been visible to hundreds of generations of coastal people at the Baltic Sea. It still is. A present maximum land uplift rate of 1 cm per year makes an uplift of the land relative to the sea of nearly 1 m during a lifetime. In flat areas this causes a considerable outward movement of the coastline, emergence of new islands, turning of bays into lakes etc. A modern map illustration of the phenomenon is given in Figure 1.

In order to understand what is going on, scientists have observed the apparent fall of sea level along the coasts, formulated ideas and constructed models of the phenomenon and the Earth, and then tested these ideas and models against the observations. Sometimes new observations have led to new ideas, sometimes new ideas have required new observations. We will here go through the development of the scientific knowledge of the phenomenon, focusing on the main modelling questions that have turned up along the journey. In the end this will lead to our present understanding of the phenomenon. This can also be seen as a typical and illustrative example of the interplay between theory and observations in scientific work in general.

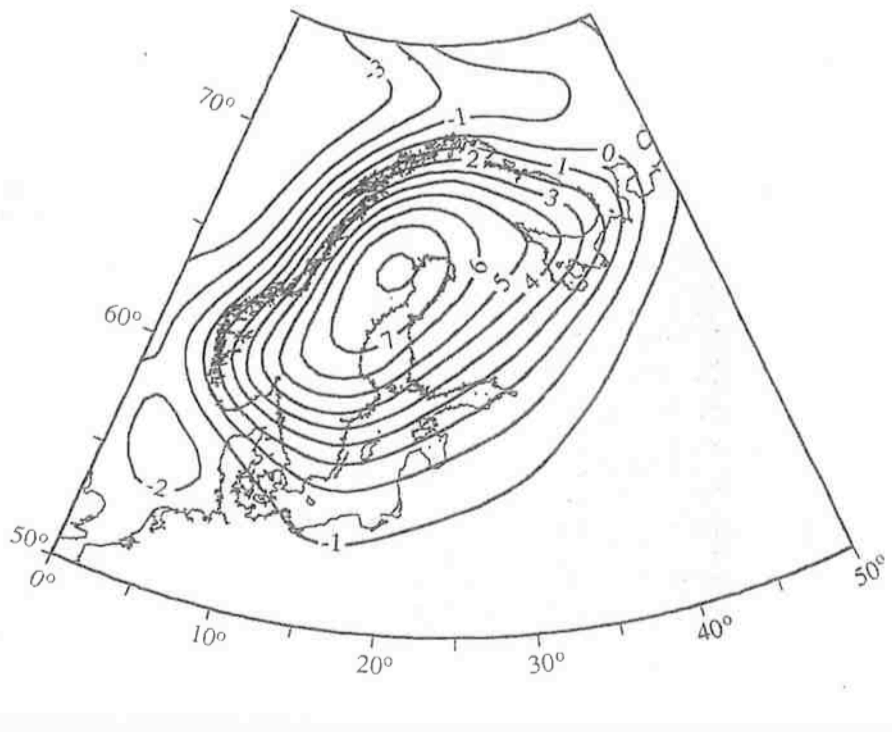

Figure 1. Map of rates of the postglacial uplift of Fennoscandia according to the model of Lambeck et al (1998a), based on instrumented sea level records.

It should be mentioned here that the text that follows is based on the author's book "The changing level of the Baltic Sea during 300 years: A clue to understanding the Earth" (Ekman, 2009).

2. Land uplift or water decrease?

The first question that arose was a very fundamental one: Is it the land that is going up or is it the water that is going down? This is not a very easy question to answer. The first written document dealing with what we now know is a postglacial rebound dates from 1491 when the town of Östhammar, on the coast of the Baltic Sea somewhat north of Stockholm, had to be moved to another locality because its harbour was no longer possible to reach by boat. In the document the problem is ascribed to a rising of the land; this might be due to the people there believing that it was a local phenomenon. Later, at the end of the 1600s, one started to investigate the phenomenon a little more systematically by collecting information from people living along the coasts around most of the Baltic Sea. Such information rather gave the impression of a lowering of the sea level of the Baltic Sea. This gave rise to three different models:

A. A general water decrease in the Baltic Sea, suggested by Hiärne (1706). This could be due to erosion of the outlet.
B. A latitude-dependent water decrease, with the water going down more in northern latitudes than in southern ones, suggested by Frisi (1785). This could be caused by an increased rotational velocity of the Earth, which in its turn would be caused by a cooling and subsequent contraction of the Earth.
C. A regional land uplift, suggested by Playfair (1802). This could be caused by interior processes in the Earth. A point here was that a land uplift is more probable since it easily allows just a regional change to take place and does not require a global one.

To settle the question more observations were needed. Celsius (1743) had succeeded in determining an approximate annual rate of the sea level change using an abandoned seal rock, but that was a special case. In 1731 Celsius had a mean sea level mark cut into a rock at the island of Lövgrund in the south-western part of the Gulf of Bothnia. Following his initiative mean sea level marks were then cut at several places along the coasts of the Baltic Sea. One century later Lyell (1835) and others could use these marks for solving the question of water decrease versus land uplift:

A. The observations do not at all yield an equal rate of change in the whole Baltic Sea. Thus a general water decrease in the Baltic Sea is ruled out.

B. Although the observations show a larger rate of change in the north than in the south, the difference is considerable within a moderate distance and the rate in the south is close to zero. Thus a latitude-dependent water decrease is unlikely.
C. The observations yield different rates of change in different parts of the Baltic Sea. Hence a regional *land uplift* clearly is the most likely phenomenon producing the observations.

3. Cooling or heating of the Earth?

Now, what could be the origin of a land uplift in the Scandinavian area? This question gave rise to three different models:

A. Cooling and subsequent contraction of the Earth, causing deformation, suggested by Berzelius (1830 & 1834).
B. Heating and subsequent expansion of the Earth, suggested by Lyell (1835a).
C. Postglacial rebound after unloading of a thick ice created during an ice age, suggested by Jamieson (1865). The Ice Age itself had been suggested a generation earlier but was not accepted until much later; see next section.

Before we proceed we may note a fascinating mixture of contradictory hypotheses. Frisi claimed that a cooling and contraction of the Earth would cause a water decrease, Berzelius claims that the same cooling and contraction will cause a land uplift. And the other way around: According to Berzelius the land uplift is caused by cooling and contraction of the Earth, according to Lyell the same land uplift is caused by heating and expansion of the Earth. This illustrates the difficulties in understanding the phenomenon. To this was then added a completely new idea of supposed effects of an ice age not yet accepted.

To solve this question more accurate observational data were needed. The mean sea level marks could have been used, but at that time one did not understand other variations of the sea level of the Baltic and so one was unable to analyse the data in a sufficiently correct way. Daily readings of sea level at established sea level stations had started in the mid 1800s, but only few of these sea level series were reliable enough. In the absence of sufficient data from "present" sea level De Geer (1888 & 1890) realized that one could use the marine limit, the highest shore-line formed after the Ice Age. This is recognizable in nature, and he produced a map showing its height in different parts of the uplift area. Later Blomqvist & Renqvist (1914) could use daily sea level readings and continuous mareograph recordings to produce a (partial) map of the present uplift rate. These two maps agreed; they could be used to solve the question of the origin of the land uplift:

A. The maps are quite regular; they do therefore not support a cooling and contraction of the Earth.
B. The maps, although smooth, show a geographical extension somewhat difficult to explain by a heating and expansion of the Earth.
C. The maps show a concentric uplift pattern over the supposed formerly glaciated area. Hence they clearly support a *postglacial rebound*, also known as *glacial isostatic adjustment*.

4. Solid or fluid Earth?

Jamieson's (1865) idea of a postglacial rebound was for a long time met with silence; it took a generation before it was accepted because of De Geer's (1888 & 1890) and Blomqvist & Renqvist's (1914) investigations. Actually the idea of the Ice Age had been presented already in 1837, so from that time it took two generations before the land uplift in the Baltic Sea area was accepted as a postglacial rebound. Why?

In order to have a postglacial rebound you need two things: a thick ice and a more or less fluid Earth. Most geologists at that time were in favour of a fluid Earth, but did not accept an ice age. Most geophysicists, on the other hand, were in favour of an ice age, but did not accept a fluid Earth. The refusal of the geologists to accept an ice age was due to difficulties in understanding the astronomical origin of such drastic climate changes. The refusal of the geophysicists to accept a fluid Earth was due to findings from tidal observations. The fact that there are quite considerable tides in the world's oceans meant that the Earth itself could not yield very much to the tidal forces, otherwise the ocean tides would be smaller. The conclusion from this was that the Earth must be a solid body, although somewhat elastic.

After having shown that the land uplift was indeed a postglacial rebound De Geer developed a method of dating raised beaches. This allowed the construction of a curve illustrating the land uplift as a function of time since the end of the Ice Age. Nansen (1921) noted that the uplift was decaying more or less exponentially; he claimed that the uplift of the crust should be accompanied by a horizontal viscous inflow of subcrustal material. The Earth must be a fluid body, although viscous. Inspired by this, Vening Meinesz (1934) and Haskell (1935) succeeded in using land uplift data from Baltic Sea level observations, in two different ways, to calculate the viscosity of the Earth. They both obtained 10^{21} Pas.

Thus there were now two contradictory models of the character of the Earth:

A. The Earth is an elastic solid. This is the information given from tidal phenomena.
B. The Earth is a viscous fluid. This is the information given from postglacial rebound.

Which view is the correct one? In this case the solution is very diplomatic:

A. The Earth behaves as an elastic solid when subject to forces of short duration – days, months, years (e.g. tidal forces).
B. The Earth behaves as a *viscous fluid* when subject to *forces of long duration* – thousands of years (e.g. ice loading).

Thus the Earth is both an elastic solid and a viscous fluid; it all depends on the time perspective. In short, the Earth is a viscoelastic body.

5. Uniform or layered Earth?

From seismology it had become clear that the Earth has a core, a mantle, and, at the surface, a relatively thin crust or lithosphere. The viscous flow should take place in the mantle, but the seismological data also showed that there are two separate mantle layers, an upper mantle and a lower mantle. This gives rise to two model possibilities concerning the viscosity of the Earth:

A. The mantle is homogeneous; it has a uniform viscosity.
B. The mantle is inhomogeneous; different mantle layers have different viscosities.

We now approach a situation where it becomes increasingly difficult to solve the model problems, both from the theoretical and the observational point of view. On one hand more advanced rebound theories, valid for a layered Earth, had to be developed. Such theories were first introduced by McConnell (1965) and, as a start of a long series of investigations, by Peltier (1974). Also of importance here was the sea level equation introduced by Farrell & Clark (1976). On the other hand more rebound data, both in space and time, and also more accurate data, were needed. The reason for this is that a characteristic problem with a layered Earth is the ambiguity of any solution that is not founded on a very large amount of data. Different combinations of mantle viscosities and lithosphere thickness might result in rather similar general uplift patterns. Thus, from the uplift data it might be difficult to resolve the model parameters in a unique way.

Now, a comprehensive geological data base for uplift curves in Fennoscandia and its surroundings was compiled by Lambeck et al (1998), and used by them to find the optimum solution for a three-layered Earth (lower mantle, upper mantle, lithosphere). Furthermore, a consistent set of present uplift rates from long-term sea level stations of the Baltic Sea and its surroundings was presented by Ekman (1996), and used by Lambeck et al (1998a) for the same purpose. The two model solutions agreed within their confidence limits. They show, as also later studies:

A. The mantle does not have a uniform viscosity.
B. The *viscosity of the lower mantle is larger than that of the upper mantle* by one order of magnitude.

To summarize the orders of magnitude: The viscosity of the lower mantle = 10^{22} Pas, the viscosity of the upper mantle = 10^{21} Pas, the thickness of the lithosphere = 100 km.

6. Symmetric or asymmetric ice?

When modelling the layered Earth it is not only the Earth itself that is modelled; also the ice resting on the Earth during the Ice Age has to be modelled. This was first done by Peltier & Andrews (1976), as a start of a series of investigations by Peltier. In reality, one tries to find a combined optimum solution for the ice and the Earth from the uplift data. The history of the melting of the ice is reasonably known from geology and glaciology. What can be modelled from the uplift data are the shape and the thickness of the ice. The shape is probably dependent on to what extent the ice was frozen to its base or not, i.e. to what extent it rested on frozen or unfrozen ground. This gives rise to two model possibilities concerning the shape of the ice:

A. The ice had a symmetric profile.
B. The ice had an asymmetric profile.

Such an ice modelling has been made together with the Earth modelling in the above Fennoscandian works by Lambeck et al (1998, 1998a). The result is quite clear:

A. The ice cannot have had a symmetric profile.
B. The *ice must have had an asymmetric profile*, higher in the north-west and lower in the south-east. This is probably related to the ice being frozen to its base in the north-west and not in the south-east.

Moreover, the maximum thickness of the ice was found to be 2000 m.

7. Land uplift and water increase?

Taking a look at the geophysical process as a whole resulting from the Ice Age and its disappearance we may summarize it in three main items:

1. The unloading of the ice causes an uplift of the land in the glaciated area together with a viscous inflow of mantle material below. (This land uplift also leads to a partial unloading of sea water causing a further uplift.)

2. The melting of the ice causes a rising level of the sea in the world's oceans. (This sea level rise also leads to an increased loading of sea water causing a lowering of the sea bottom.)

3. The redistributions of matter through the above processes lead to changes in the gravity field causing corresponding changes in the geoid and, thereby, in the level of the sea.

Item 1 is a still on-going process, as is also item 3. Item 2 principally ended long ago when the large ice sheets had melted. However, due to present climate change leading to melting mountain glaciers (and thermal expansion of sea water), item 2 is still relevant. It becomes important when analysing present uplift rates from sea level records. The present *climatic rise of sea level* in the Baltic Sea area can be estimated together with the above quantities as in Lambeck et al (1998a). The same phenomenon can also be studied through the longest sea level series in the world, that of Stockholm commencing 1774, as in Ekman (2009). Combining these two methods (and also others), he arrives at a climatic sea level rise of 1 mm/year during the past century, and close to 0 mm/year during the earlier centuries. In addition to that we have the gravitational rise of the sea level according to item 3, i.e. a *rise of the geoid*, amounting to ½ mm/year, as determined by Ekman & Mäkinen (1996).

8. The past and the future

In the past, as is clear from above, sea level data – both from present sea level and from ancient raised beaches – have formed the main observational foundation for modelling the postglacial rebound. In the future, in addition to sea level data, satellite positioning data and gravity data will play an important role, as they have already started to do. The increased amount of hopefully accurate data might enable improved studies of the viscosity structure of the Earth, both vertically and horizontally, and of the character of the ice load. It is important that these things are modelled together. However, at the same time the ambiguity problem mentioned above will increase, so it will not be an easy task.

With reliable models of the postglacial rebound we can also look into the past from the historical and archaeological point of view. Reconstructing old shorelines is an essential part of understanding the historical development of the Nordic area through the millennia. In principle we could in the same way also look into the future. However, the future is much more difficult to predict because of a large uncertainty: that of future climate changes influencing the level of the sea.

References

Berzelius, J (1830 & 1834): Årsberättelse om framstegen i physik och chemie. Kongl. Vetenskaps-Academiens årsberättelser om vetenskapernas framsteg, 1830 & 1834, 1-272 & 1-411.

Blomqvist, E, & Renqvist, H (1914): Vattenståndsiakttagelser vid Finlands kuster. Meddelanden från Hydrografiska Byrån vid Överstyrelsen för Väg- och Vattenbyggnaderna i Finland, 1, 429 pp. (Also in German: Wasserstandsbeobachtungen an den Küsten Finlands. Fennia, 37/1, 433 pp.)

Celsius, A (1743): Anmärkning om vatnets förminskande så i Östersiön som Vesterhafvet. Kongl. Swenska Wetenskaps Academiens Handlingar, 4, 33-50.

De Geer, G (1888 & 1890): Om Skandinaviens nivåförändringar under qvartär-perioden. Geologiska Föreningens i Stockholm Förhandlingar, 10 & 12, 366-379 & 61-111.

Ekman, M (1996): A consistent map of the postglacial uplift of Fennoscandia. Terra Nova, 8, 158-165.

Ekman, M (2009): The changing level of the Baltic Sea during 300 years: A clue to understanding the Earth. Summer Institute for Historical Geophysics, Åland Islands, 155 pp. (Accessible also online from www.historicalgeophysics.ax.)

Ekman, M, & Mäkinen, J (1996): Recent postglacial rebound, gravity change and mantle flow in Fennoscandia. Geophysical Journal International, 126, 229-234.

Farrell, W E, & Clark, J A (1976): On postglacial sea level. Geophysical Journal of the Royal Astronomical Society, 46, 647-667.

Frisi, P (1785): Paulli Frisii operum, 3, cosmographiam, physicam, et mathematicam continens. Milano, 561 pp.

Haskell, N A (1935): The motion of a viscous fluid under a surface load. Physics, 6, 265-269.

Hiärne, U (1706): Den beswarade och förklarade anledningens andra flock – om jorden och landskap i gemeen. Stockholm, 284 pp.

Jamieson, T (1865): On the history of the last geological changes in Scotland. Quarterly Journal of the Geological Society of London, 21, 161-203.

Lambeck, K, Smither, C, & Johnston, P (1998): Sea-level change, glacial rebound and mantle viscosity for northern Europe. Geophysical Journal International, 134, 102-144.

Lambeck, K, Smither, C, & Ekman, M (1998a): Tests of glacial rebound models for Fennoscandinavia based on instrumented sea- and lake-level records. Geophysical Journal International, 135, 375-387.

Lyell, C (1835): On the proofs of a gradual rising of the land in certain parts of Sweden. Philosophical Transactions of the Royal Society of London, 125, 1-38.

Lyell, C (1835a): Principles of geology, 2, 4th edition. London, 465 pp.

McConnell, R K (1965): Isostatic adjustment in a layered Earth. Journal of Geophysical Research, 70, 5171-5188.

Nansen, F (1921): The strandflat and isostasy. Skrifter utgit av Videnskaps-selskapet i Kristiania, Matematisk-naturvidenskabelig klasse, 1921, 313 pp.

Peltier, W R (1974): The impulse response of a Maxwell Earth. Reviews of Geophysics and Space Physics, 12, 649-669.

Peltier, W R, & Andrews, J T (1976): Glacial isostatic adjustment – I: The forward problem. Geophysical Journal of the Royal Astronomical Society, 46, 605-646.

Playfair, J (1802): Illustrations of the Huttonian theory of the Earth. Edinburgh, 528 pp.

Vening Meinesz, F A (1934): Gravity and the hypothesis of convection-currents in the Earth. Koninklijke Akademie van Wetenschappen te Amsterdam, 37, 37-45.

ISSN 1798-1883 (print)
ISSN 1798-1891 (online)