The Changing Level of the Baltic Sea during 300 Years: A Clue to Understanding the Earth

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Åland Islands

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www.historicalgeophysics.ax

ISBN 978-952-92-5241-1

Printing original by Ben Johans, PQR

Printed by Logotipas

Published by the Summer Institute for Historical Geophysics, Äppelträdgården E, Haraldsby, AX – 22 410 Godby, Åland Islands. See also above.

Cover picture: The Stockholm sluice, where systematic sea level observations started in 1774. (Painting by Anders Holm in 1780, City Museum of Stockholm.)

Contents

Preface

This is a scientific book spanning several Earth sciences: from solid geophysics through oceanography to climatology. Yet it is not an ordinary scientific book. It has, in certain respects, a somewhat unusual character.

First, the book is specialized and general at one and the same time. What we study here is just one quantity, the sea level of the Baltic Sea. From this quantity, as observed during three centuries, we are able to draw conclusions about the behaviour of our Earth as a whole: its interior, its oceans, and its atmosphere. Thus, historical data from the Baltic Sea are used to solve modern Earth science problems of a more global character. This is the fundamental idea of the book.

Second, the book gives a historical perspective on discoveries and solutions of the sea level problems. Things are explained by describing how they have actually been found out (or not found out), starting from the very beginning, sometimes commenting on old results from a modern point of view. Original scientific sources are used throughout. This means throwing light also on important works being long since forgotten by modern scientists.

Third, in order to broaden the outlook in somewhat unexpected directions, some special aspects related to the sea level changes are included at the end of the book.

The book is intended for reading by a wide range of geoscientists or other people with a professional interest in the Earth and its changes. The reader is assumed to have an elementary knowledge of basic Earth science, but not to know anything about sea level problems. The reading of the book will be facilitated by understanding nature's own language, mathematics, at the level of a novice at a university. In some cases more advanced mathematical concepts occur in the text; these can simply be passed over by those who are not familiar with them. The book might also be of interest for historians of science, but they should be aware that this is a book about science rather than about history of science.

There are a number of quotations in the text, serving to illustrate and bring to life important points in the scientific development. Their translations into English are due to the present author. Some of the older quotations have had to be translated rather freely to make them readable; however, great care has always been taken to convey the original message in a correct way.

References in the text are given by names and years within brackets; when years occur without brackets they relate to historical information. In order to make the scientists and other persons referred to less anonymous, they have all been given a brief characterization, such as British oceanographer and climatologist, German-Swedish harbour engineer etc. The reference list at the end is not ordered alphabetically, as would be normal, but chronologically. This has made it possible to give a chronological overview of all the published works used.

Most of the author's own research included here has been performed within his private one-man-institute, the Summer Institute for Historical Geophysics, on the Åland Islands in the Baltic Sea. Some parts of the early research have been made while the author was working at the Geodetic Research Division of the National Land Survey of Sweden.

A number of people have been helpful during the work with this book and the research leading up to it. I would like to thank the persons who have read the manuscript and given constructive comments on it: Kurt Lambeck at the Research School of Earth Sciences at the Australian National University, Jaakko Mäkinen at the Finnish Geodetic Institute, Anders Stigebrandt at the Oceanographic Department at the Göteborg University in Sweden, and Philip Woodworth at the Permanent Service for Mean Sea Level in Great Britain. To find the old literature I have had great benefit of the library of the Royal Swedish Academy of Sciences, partly deposited with the University Library of Stockholm, and also of the University Library of Uppsala and the library of the former Geographical Survey Office of Sweden. To find original sea level data not published I had, in earlier stages of the work, great use of the City Archives of Stockholm, and also of the Danish National Archives and the archives of the Swedish Meteorological and Hydrological Institute.

My final thanks go to those sea level observers, long since dead, whose faithful work in former centuries at sluices, light-houses, harbours and scientific institutions has made this book possible.

Åland Islands, at the sea shore, midsummer 2008

Martin Ekman

1. Introduction: What is so interesting about the Baltic Sea level?

1.1 Remarkable phenomena

This is a book about the sea level of the Baltic Sea. It might seem as a very specialized subject. In fact it is not, on the contrary. The fascinating thing is that this single physical quantity – the Baltic Sea level – tells us a lot about the planet we live on. In that sense the subject is very wide. The book will deal with most parts of the Earth: its mantle, its crust, its water, its ice, its atmosphere.

The sea level in the Baltic Sea exhibits a number of remarkable phenomena. These phenomena are often special to the Baltic Sea (and sometimes the adjacent part of the North Sea) but, as mentioned, they are of a much wider, even global, interest. The most important Baltic Sea level phenomena, all of them treated in this book, are the following.

Postglacial rebound or postglacial land uplift (sometimes known as glacial isostatic adjustment). This is the ongoing rise of the crust due to unloading of the ice cover at the end of the Ice Age. From long series of sea level observations, at stations distributed over the Baltic Sea area, rates of the uplift can be determined. The uplift rates allow conclusions on both the thickness of the disappeared ice and on the internal structure of the Earth, especially the viscosity of the Earth's mantle. The latter is of importance for understanding also the driving mechanism behind continental drift (plate tectonics).

Climatic (global) sea level rise (sometimes known as eustatic sea level rise). This is the ongoing rise of global sea level due to melting of glaciers and thermal expansion of sea water. Using the same sea level data as above and, in particular, the extremely long sea level series of Stockholm in the central Baltic, this effect and its change over a long time can be studied. This is of importance for understanding the effects of global warming.

Winter sea level changes (*inter-winter sea level oscillation* and others). These are the changes of sea level due to seasonal variations in climate. In the Baltic Sea it turns out that winters, and especially winds during winters, play a key role in the sea level variations. Using again the long Stockholm sea level series, several changes in winter climate over the last centuries can be detected. This is of importance for understanding large scale changes in the atmospheric circulation.

Pole tides. This is the small periodical variation of sea level due to polar motion, a somewhat circular motion of the pole relative to the crust with a period of 14 months. In the Baltic, however, this effect turns out to be larger than predicted, the reason being that a variation in the wind field of the same period seems to be operating here. Again, the long Stockholm series reveals changes in this strange atmospheric effect over the last centuries.

Mean sea surface topography. This is the deviation of the mean sea surface from a surface perpendicular to the plumb line. In the Baltic Sea this deviation is mainly caused by considerable differences in salinity of the sea water between different parts of the sea. This effect can be determined from long series of sea level observations distributed over the Baltic Sea area and connected through levellings (height measurements). It is of importance for testing oceanographic models of the salinity distribution and transportation in the Baltic Sea and its connection to the ocean.

1.2 Remarkable data

Globally speaking, a device for observing sea level is usually called a tide gauge. In the Baltic Sea, however, there are practically no tides, mainly because of the choking effect of its narrow and shallow entrance in the Danish straits. Hence what is internationally known as a tide gauge will here be called a *sea level gauge*, or a *sea level station*. A sea level gauge that is read by eye at certain intervals will sometimes be called a *sea level scale*, while a sea level gauge that is recording automatically and continuously will sometimes be called a *mareograph*.

The Baltic Sea has an exceptional concentration of long and reliable sea level records, both from sea level scales and mareographs. Many of them date back to the 1800s, one of them even to the end of the 1700s.

Figure 1-1. The so-called Celsius rock at the island of Lövgrund with mean sea level marks from 1731, 1831 and 1931.

There are also, dating further back in time, *mean sea level marks*, marks cut in rocks to show approximate mean sea level at some specified year.

The cutting of mean sea level marks was initiated in 1731, at *Lövgrund* in the south-western part of the Gulf of Bothnia; see Figure 1-1. They were used for studying what we now know as the postglacial land uplift. These marks lacked a vertical scale where sea level could be read.

A sea level scale was in operation during the year 1746 at Härnösand further north, allowing the first conclusions on meteorological effects on sea level. More permanent sea level scales were established for practical purposes in the 1700s at the three capitals on the coasts of the Baltic Sea: Stockholm in Sweden (a sluice), København in Denmark (a dock), and Kronstadt at St. Petersburg in Russia (a naval base). Only in *Stockholm* were the observations at that time reasonably reliable and archived, this starting in 1774; most of the observations are still preserved. This makes the Stockholm sea level series the longest one in the world; see further Section 1.3.

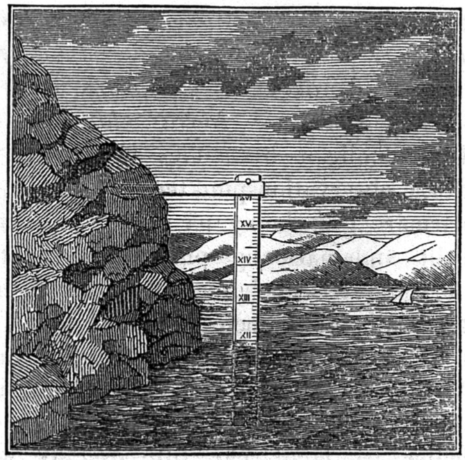
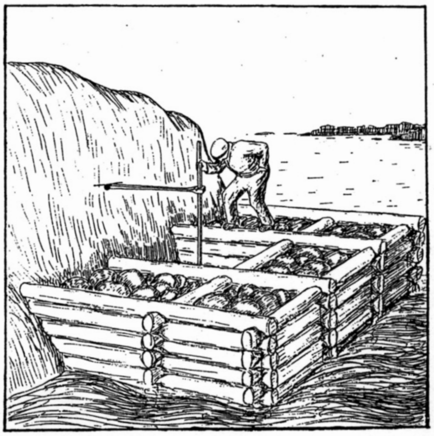


Figure 1-2. Sea level scale around 1850 (Erdmann, 1856).



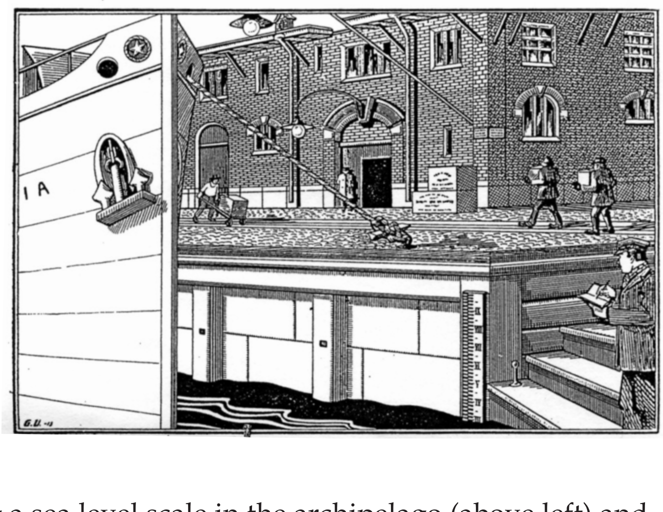


Figure 1-3. Reading a sea level scale in the archipelago (above left) and in a harbour town (below right) at the end of the 1800s. Note the different styles of the observers. (Renqvist, 1931, and Blomqvist & Renqvist, 1914.)

Figure 1-4. The mareograph of Stockholm, still in operation.

Systematic sea level observations on a larger scale were initiated in Germany (Prussia) in 1811, at several river mouth harbours along the coast, following an instruction by the water engineer Johann Albert Eytelwein (1810). Reliable sea level data from a few of them have survived until today, the most complete record being that of *Swinemünde* (nowadays Świnoujście in Poland). Similar observations were started at light-houses and pilot stations in Sweden in 1849 and at about the same time in Finland, see Figure 1-2 and also the illustrations in Figure 1-3. Most of these sea level records are still preserved, but only few of them can be considered reliable.

Scientifically controlled mareographs were introduced in most countries around the Baltic about 1890, a typical example being shown in Figure 1-4. Since then we have a large number of sea level records that are both reliable and preserved. The mareograph data are normally stored at national hydrographic institutes and also at the Permanent Service for Mean Sea Level (PSMSL), the international sea level institute in England.

Table 1-1. The oldest sea level stations, their reliable time spans, and main published data sources. The letter A denotes annual means only, the letter M denotes monthly means as well (an asterisk indicates partly erroneous or missing data).

Stockholm	1774 –	Erdmann (1847 & 1853)	A*
		Lilienberg (1891)	M*
		Ekman (2003)	M
Swinemünde (Świnoujście)	1811 –	Seibt (1881 & 1890)	M
		Montag (1964)	M
Pillau	1816 – 1944	Bannasch (1835)	A
		Schreiber (1875)	A*
		Hahn & Rietschel (1938)	A
Kolberg	1825 – 1935	Anderson (1898)	M
		Hahn & Rietschel (1938)	A
Kronstadt	1841 – 1916	Saltykov (1888)	M
		Bogdanov et al (2000)	M
Wismar	1849 –	Paschen (1882)	A
		Liebsch (1997)	M
Grönskär	1849 – 1930	Forssman (1876)	M*
		Ekman (in prep)	M
National compilations		Forssman (1876)	M*
		Renqvist (1931)	M*

In Table 1-1 we give an overview of the oldest reliable sea level stations with their time spans and data sources (and of a few national compilations of some of the old sea level data).

1.3 The world's longest sea level series

As mentioned the *Stockholm sea level series* constitutes the longest sea level series in the world. (The Amsterdam sea level series is the oldest one, but that was discontinued a long time ago.) The Stockholm series will play a crucial role in this book, not only because of its length but also because of its special oceanographic position in the Baltic, explained later on. Therefore we will here give some historical information on the Stockholm series.

The foundation of Stockholm in the middle of the 13th century was mainly a consequence of the postglacial land uplift. At that locality a part of the Baltic Sea was gradually being cut off and turned into Lake Mälaren. Due to erosion of its outlets, however, the lake level continued to be close to the sea level. Lake Mälaren thus formed an intermediate between lake and sea, its outlets causing problems for the important shipping. In the 17th century it became necessary to build a sluice with lock gates here.

At the 1772 session of the Swedish parliament there were complaints that the level of the lake was often too high, causing flooded fields. By order of King Gustaf III a hydrographic investigation of the outlets of the lake was undertaken in the next year, by the land surveyor and hydrographer Jonas Brolin (1773). The following year, 1774, systematic observations of the water levels started on both sides of the sluice, i.e. both in the lake and in the sea. A picture of the sluice is shown in Figure 1-5; see also Figure A-1 in Appendix. The original water level scales were cut into the stone walls of the sluice; later on separate wooden scales were put up.

Although there was an ambition to keep the lake not too high, it was equally important to keep it not too low. In the latter case the sea level could, especially in autumn, be higher than the level of the lake, thereby making the use of the sluice difficult. These events were noted together with the water level readings by the special word ”uppsjö”, approximately meaning ”sea higher”. They provide a valuable possibility to

Figure 1-5. The Stockholm sluice in 1780, six years after the beginning of the sea level observations there. The picture shows an occasion when the level of the lake was exceptionally high. (Painting by A Holm 1780, City Museum of Stockholm.)

check the zero levels of the gauges. The water level readings were collected in water level books and other documents, now preserved in the City Archives of Stockholm; an example is shown in Figure 1-6.

In 1849 the Royal Swedish Academy of Sciences initiated sea level observations at the lighthouse Grönskär, on a solid rock distant in the Stockholm archipelago. These observations were performed on a sea level scale with great care by the lighthouse keeper. His water level books are stored in the Archives of the Swedish Meteorological and Hydrological Institute. Comparisons between the Stockholm and Grönskär data provide an important additional means for checking the zero level of the Stockholm gauge.

In 1889 the Nautical-Meteorological Bureau – a predecessor of the Swedish Meteorological and Hydrological Institute (SMHI) – established

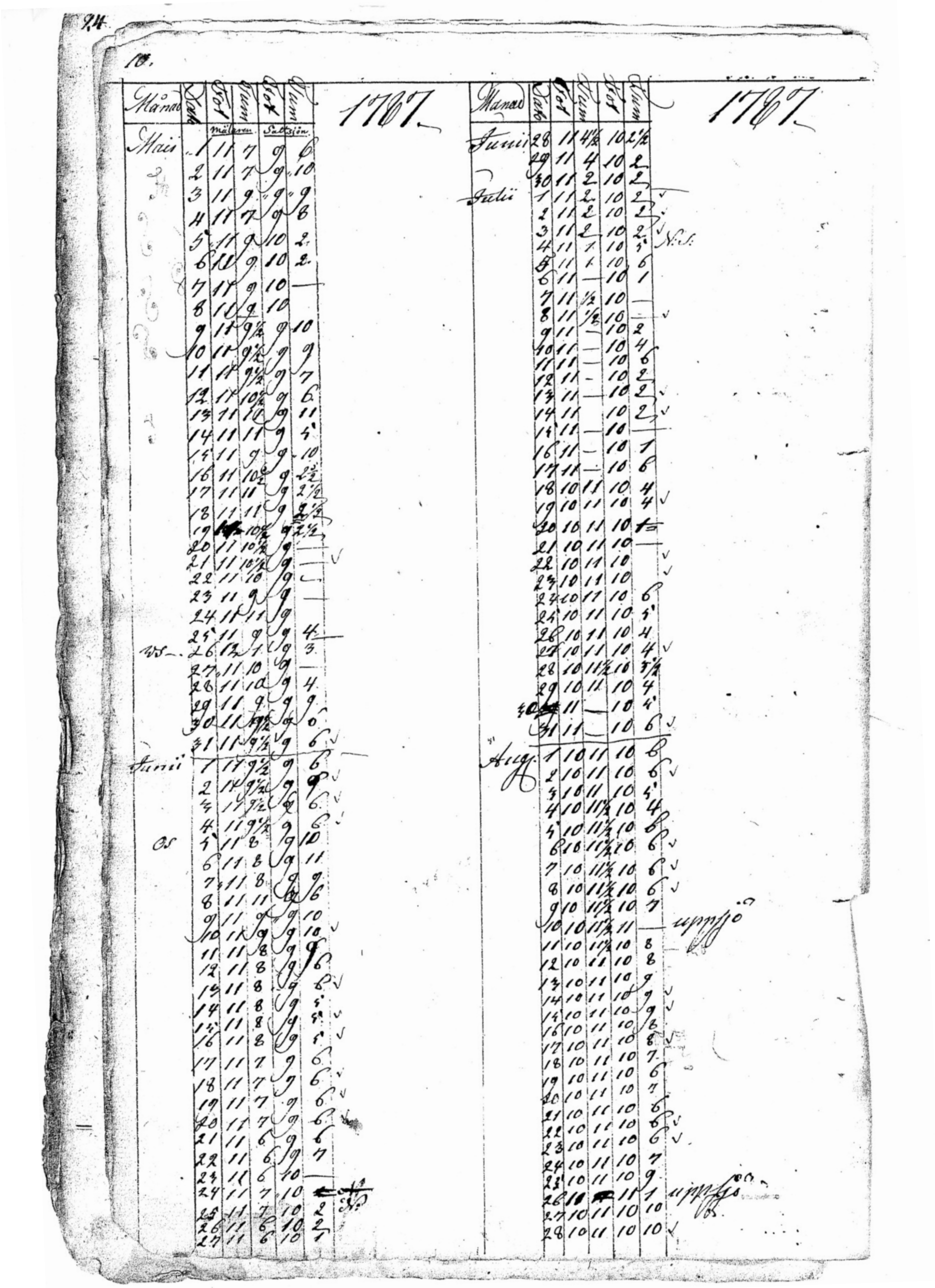


Figure 1-6. Water level observations at the Stockholm sluice during a part of 1787. The columns contain (from left to right) date, lake level in feet and inches, and sea level in feet and inches.

a continuously recording mareograph in the bedrock of a small island in Stockholm (Skeppsholmen) close to the sluice. This mareograph has since then recorded the Stockholm sea level; see Figure 1-4.

The observations of the Stockholm sea level have been made with the following approximate frequencies:

1774 – 1804, 1812 – 1841	Weekly
1805 – 1811, 1842 – 1888	Daily
1889 –	Hourly

Because of the very special oceanographic conditions in the central part of the Baltic Sea, with only long-term sea level variations as explained later on, even weekly observations are sufficient to produce a reliable monthly mean. This is contrary to most other places in the world. For the years 1812 – 1824 the author has succeeded in filling a gap in the data by transforming sea levels from København to Stockholm.

The resultant series of monthly and annual mean sea levels has been published by the author (Ekman, 2003), together with details on the calculation of the series. For easy reference the list of monthly and annual mean sea levels is reprinted here; see Appendix.

1.4 Sea level relative to what?

Before entering into the main contents of the book we also need to say something about what we actually mean by sea level. Sea level has to be defined relative to something – but relative to what? There are basically four possibilities.

Sea level relative to the crust. This is what is actually measured when sea level is observed on a vertical scale fixed in the crust (land), either by reading the sea level at certain intervals or by recording it continuously. Sea level in this sense will be influenced both by vertical movements of the crust and by vertical movements of the sea surface.

Sea level relative to the reference ellipsoid (or the centre of gravity). This is what can be measured from a satellite; the reference ellipsoid is an ellipsoid of revolution of the Earth centred at the Earth's centre of gravity. Sea level in this sense will be influenced by vertical movements of the sea surface, irrespective of their origin, but not by crustal movements.

Sea level relative to the geoid. This is what can be determined from levellings of the sea surface; the geoid is an equipotential surface in the Earth's gravity field, i.e. a surface everywhere perpendicular to the plumb line, approximating long-term mean sea level. Sea level in this sense will be influenced by vertical movements of the sea surface due to oceanographic and atmospheric effects, but not by movements due to gravitational changes (mass changes) of the Earth.

Sea level relative to normal sea level. This is the quantity reported in marine weather forecasts; normal sea level is the mean sea level. Sea level in this sense will be influenced by vertical variations of the sea surface due to oceanographic and atmospheric variations, but not by a secular rise or fall of the sea surface.

In this book the concept of sea level is used in all senses, depending on what phenomenon is treated. If necessary, the meaning of the concept is specified; otherwise it is usually obvious from the context. In the title of the book the concept of sea level is used in the first sense, i.e. in the sense of what is actually observed. Therefore, this book will deal with vertical movements of both the crust and the sea surface.

2. Is the land going up or the water going down?

2.1 Harbour problems and relocation of towns

The oldest existing document containing a piece of information about the level of the Baltic Sea is probably a rune stone from the Viking Age, at the village of Runby north-west of Stockholm. The runic inscription is due to the Viking woman Ingrid (c. 1050). She informs the reader that here she has had a ”laðbro” constructed. The most probable interpretation of this word is ”loading bridge”, i.e. a quay or wharf, and her text then reads:

”Ingrid had the loading bridge made and the stone carved after Ingemar, her husband, and after Dan and after Banke, her sons. They lived in Runby and there owned a farm.”

Ingrid’s runic text was cut on an erratic boulder from the Ice Age, situated close to a Viking sailing route at the Swedish coast of the Baltic Sea. On the other side of the boulder she had a remark written: ”This shall stand as a memorial as long as humans live.” Today, one thousand years later, the boulder is still there and Ingrid’s runes are still there to read. One thing, however, is no longer there: the water at which the loading bridge must have been built. The water is now several kilometres away, because of the postglacial rebound. It can be calculated that, since 1050, the land here has risen by nearly 5 m (according to Chapters 3 and 4; see also Section 8.3). Reconstructing the shore-line of that time shows Ingrid’s rune stone to be situated at what was then the inner part of a sheltered bay connected to one of the main Viking sailing routes. This must have been an excellent place for a small harbour construction.

The first written document dealing with a *change of the level of the Baltic Sea* dates from 1491. That year four townsmen from Östhammar, a town on the coast of the Baltic Sea somewhat north of Stockholm, went to the Swedish government in Uppsala to complain that their harbour was no longer possible to reach by boat. At this time Sweden was in a union with Denmark and Norway, their common king residing in Denmark. Under these circumstances the government of Sweden was headed by the

Swedish archbishop in Uppsala, Jacob Ulfsson. The four townsmen (Anders Botvidsson, Nils Hansson, Anders Persson and Jöns Andersson) therefore went to him.

Jacob Ulfsson was a highly educated man, having studied for a long time at universities abroad. Back in Sweden he founded the first university in the Nordic countries, that of Uppsala, and became its first head. Now, in response to the complaints from the townsmen of Östhammar, Jacob Ulfsson and his government (1491) issued a resolution, in which the harbour problems are described:

”During recent years the land has grown outside the town at the sea, so that where some years ago a cargo boat of five or six Swedish läster [about 15 tons] could come from the sea into the town of Östhammar not even a fishing-boat can go nowadays. And the land is still growing and rising every year.”

Similar complaints had been put forward several times, and the townsmen asked for permission to relocate the whole town. Such a permission was granted, and the resolution now ordered the people of Östhammar to abandon the town and to found a new one, Öregrund, at a better harbour locality instead; see Figure 2-1.

The cited text above is the earliest description of the phenomenon that we today know as the *postglacial rebound*, or the *postglacial land uplift*. The location of the Östhammar harbour probably stemmed from the 1100s. By the end of the 1400s the people then must have been subject to a land uplift of nearly 2 m, fully sufficient to destroy their shallow harbour. Today, what was their harbour is dry land. In the new town of Öregrund one of the original buildings from 1491, thus erected because of the land uplift, is still to be seen, namely the church.

One and a half centuries later the same problem appeared, but now further north, at the northern part of the Gulf of Bothnia. Here the harbour town of Luleå had to be relocated. Also here the townsmen and their mayor asked for permission to relocate the town. In response to that, Queen Christina (1648) issued a resolution, stating that the town would have to be relocated because its position was distant from the water.

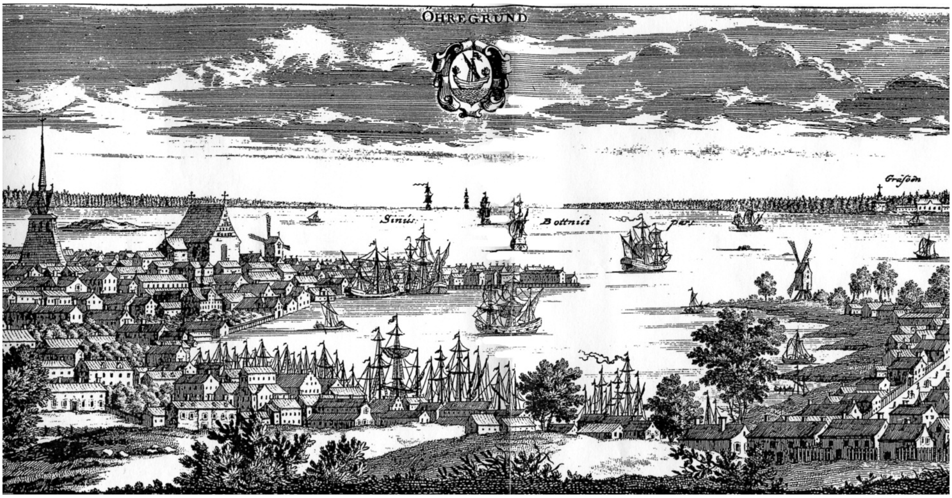


Figure 2-1. The town of Öregrund (in the 1600s), relocated because of the land uplift. Its harbour and church stem from the relocation in 1491. (From Dahlbergh's collection of engravings "Suecia antiqua et hodierna".)

The location of the Luleå harbour stemmed from the 1300s. By the middle of the 1600s this shallow area must have been subject to a land uplift of almost 3 m, clearly making it necessary to move the town and its harbour. The new town retained the old name, whereas the former town still exists as an old market place called Gammelstaden, ”The old town”.

The first attempt to investigate the phenomenon a little more systematically was made by Elias Brenner and Urban Hiärne. Brenner was a Swedish historian, born and raised close to the Gulf of Bothnia, on its Finnish side. Hiärne was a Swedish scientist in medicine and chemistry, interested in investigating the Earth. (Besides, he had no less than 26 children.) Hiärne had sent out a questionnaire to governors, bishops and other state officials in different parts of Sweden and Finland (at that time belonging to Sweden) concerning various phenomena in nature. He was particularly interested in collecting information on possible changes with time.

From the answers Hiärne (1706) concluded that the level of the Gulf of Bothnia and probably the whole Baltic Sea was gradually falling. There were two kinds of evidence for this along the coasts, as illustratively in-formed by Brenner (1694), with his first hand knowledge from the Gulf of Bothnia:

”From old times one has noticed and experienced how large bays of the sea gradually turn into land. Where people in several places 70 or 80 years ago could sail freely with small boats, now every year hundreds of loads of hay are gathered. … One has also found that the waters up to one Swedish mile [c. 10 km] or more off the coast gradually become more unsafe. This has been experienced by several navigators whose ships have run aground and been damaged, where never before any cliffs or grounds have been detected.”

Thus, where earlier generations were used to sail there was no longer any water, or too little water.

Hiärne not only collected evidence for a change of the level of the Baltic Sea; he also made an attempt to explain the phenomenon. According to him, the many rivers falling into the Gulfs of Bothnia and Finland as well as the Baltic proper caused the sea water earlier to be much higher than now. This water must have tended to stream to the North Sea, thereby in the long run eroding and widening the outlet. As a consequence, the surface of the Baltic Sea should have become much lower.

We may note here that while the townsmen of Östhammar/Öregrund in 1491 describe the phenomenon as a rising of the land, Hiärne two centuries later describes it as a falling of the sea level. The townsmen probably considered that their harbour problem was a fairly local one, giving them the impression of a *land uplift*. Hiärne, on the other hand, found that the phenomenon could be observed around most of the Baltic Sea and thus was a more general one, giving him the impression of a *water decrease*.

2.2 The scientific use of seal rocks

Although there were by now a lot of indications of a gradual change of the sea level in the Baltic, there was still no proof of it in a more scientific sense. To prove that such a phenomenon was going on one would need some kind of determination of mean sea level at some specific time long ago, allowing it to be compared with a modern determination.

One generation after Brenner and Hiärne, Anders Celsius (1743) presented an original and useful method to deal with this problem. Celsius, today mostly known for his temperature scale, was a Swedish geophysicist and geodesist. He had made travels along the coast of the Gulf of Bothnia, the northernmost of them as a member of the famous French expedition to determine the flattening of the Earth. Celsius was aware of the existence of so-called *seal rocks* along the coast. These are rocks in the sea water used by seals to rest on. Celsius realized two interesting things about the seal rocks. First, to make it possible for the seals to get up on the rock, its top has to be close to mean sea level. Second, since a seal rock might be economically important as a place for shooting seals, there are in some cases written documents on the ownership of such a rock.

Celsius now managed to find four seal rocks useful for scientific purposes. They were situated in widely different places at the coast of the Gulf of Bothnia, two of them at the Swedish coast and two at the Finnish coast. These seal rocks were explicitly mentioned and valued in old inheritance documents and bills of sale. However, in later taxation certificates they were declared unusable because they were too high above the water or standing on dry land. Celsius' conclusion was that mean sea level must be falling. People had, unwittingly, recorded this phenomenon in legal documents!

Now, one abandoned seal rock was especially rewarding because it could be identified and measured. This rock was situated in the southwestern part of the Gulf of Bothnia, at the island of Iggön. Celsius (1743) writes as follows, referring to his sketch of the rock which is shown here as Figure 2-2:

”Formerly there lived a peasant here called Rik-Nils [Rich Nils] because of plentiful fishing. He caught seals on the top *a* of this rock, where in the beginning the seals could get up when the sea was still, in calm weather, and was equal to AB. But later, when the water in his time decreased and fell to CD, the seals used to lie on *b*. And since the top *a* then prevented Rik-Nils from shooting the harpoon in the seals when coming from the island, he burnt out of the rock the whole piece down to *d*, in winter when the water generally is at its lowest. There can still be seen clear traces of this and it is also confirmed by all Rik-Nils' descendents. The sons of Rik-

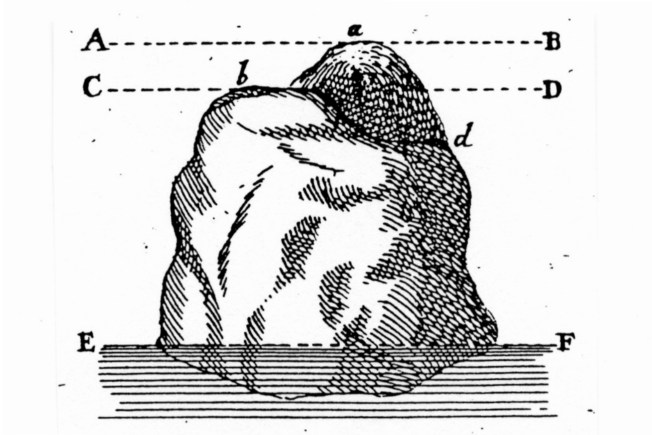


Figure 2-2. The abandoned seal rock at Iggön (Celsius, 1743).

Nils then purchased this island from the Crown and they have received a taxation certificate of this by King Jan [Johan] III, dated 1583, March 24th. … The rock was burnt by the father about 20 years before his sons purchased the island, i.e. in 1563. But in 1731, in summer when the water was approximately at its mean level, the horizontal line EF of the sea was found to be 8 [Swedish] feet below CD. This is thus the amount the water has fallen in 168 years."

With this crude method Celsius succeeded in arriving at a *rate of the water decrease*. Converting Swedish feet into cm his value becomes

$$\dot{H} = \frac{237}{168} = 1.4 \text{ cm/yr}$$

From modern methods we have $\dot{H} = 0.8$ cm/yr (Chapters 3 and 4). Thus Celsius' value, although too large, is of the right order of magnitude. This is the first determination of the rate of what we today know as the post-glacial land uplift. Celsius pointed out that the phenomenon would make it essential for pilots to remeasure the depths every 20 years or so. In the long run it would reshape the whole coastal geography of the Baltic Sea.

Celsius' result caused a considerable scientific interest. Support for the water decrease came from two of his compatriots, the botanist Carl Linnaeus (1745) and the physicist and medical officer Nils Gissler (1747).

On the island of Gotland in the Baltic Sea Linnaeus had come across a sequence of ridges, all parallel to the coast, which he interpreted as old shore-lines having successively lost contact with the sea because of the water decrease. Further north Gissler studied similar sequences of shore-lines, supposing, quite correctly, that they might be formed by severe storms occurring with intervals of many decades. This would also agree reasonably with Celsius' value of the rate of the water decrease. Opposition, on the other hand, came from the Swedish-Finnish bishop and scientist Johan Browallius (1755). He tried to explain Celsius' observations as what we today call systematic and random errors (thereby also defending the biblical view of the history of the Earth).

A completely different way of looking at the whole phenomenon was presented by the Swedish-Finnish land surveyor Ephraim Runeberg (1765) and the Swedish astronomer Bengt Ferner (1765), independently of each other. They suggested the possibility of the water decrease being in reality a *land uplift*. Runeberg's main argument for a land uplift was based on observations of the bedrock, especially in mines. From the bedrock's structure it could be seen that movements in the bedrock must have taken place. Ferner's way of arguing was similar but somewhat less clear.

Up till now the phenomenon in the Baltic Sea had been a matter only for people living there, whether they were seamen or scientists. But from now on it would attract international scientific attention. The Italian mathematician Paolo Frisi (1785) had learnt about the phenomenon through Ferner and got interested in it. Frisi considered the idea of a land uplift unlikely because of the lack of major earthquakes in the area. Instead he presented a new idea on the origin of a water decrease. He stated that the Earth was gradually cooling and, thereby, contracting. This would cause an increase in the rotational velocity of the Earth, leading to an increased flattening of the global sea surface, i.e. to a lowering of the sea level in polar areas.

On the other hand, a growing insight that interior processes of the Earth played an important role in the formation of rocks and in the evolution of the Earth made the Scottish mathematician and physicist John Playfair (1802) favour a land uplift. His point 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.

Obviously it is very difficult to discriminate between a lowering of the sea level and a rising of the land, since there is no fixed point on the Earth's surface to which the vertical changes of the sea or the land can be referred. This was realized already at that time. How, then, should one be able to judge whether the land was going up or the water going down? Well, a solution would be to measure the rate of the phenomenon over a larger area, in this case over the whole Baltic Sea, during a long time. This would basically give three possibilities:

1. The same rate of change in the whole Baltic Sea would point to a general water decrease in the Baltic, as suggested earlier by Hiärne.

2. A larger rate of change in the north than in the south would point to a latitude-dependent water decrease, as suggested by Frisi.

3. Different rates of change in different parts of the Baltic Sea would point to a regional land uplift, as suggested by Playfair.

2.3 Sea level marks and their significance

Let us return for a while to the pioneering work of Celsius (1743). Here he informs that he has had a special *mean sea level mark* cut into a former seal rock at the island of Lövgrund, in the south-western part of the Gulf of Bothnia. The mark consists of a horizontal line with the year 1731 above. It was cut in summer when the sea was close to its mean level (today we can estimate that it was placed about 10 cm too high). Celsius explicitly states that the purpose of this mean sea level mark is to make it possible for future generations to measure the phenomenon of the water decrease with greater accuracy. The rock, nowadays mostly known as the *Celsius rock*, is depicted in Chapter 1 (Figure 1-1).

Two decades later a corresponding sea level mark was cut into a rock in the north-western part of the Gulf of Bothnia by Samuel Chydenius (1749), a Swedish-Finnish chemist. On the eastern coast of the gulf this kind of work was continued by Jacob Gadolin (1751), a Swedish-Finnish geodesist. And within the next two decades another five sea level marks had been cut along the coasts, four of them in different parts of the Gulf of Bothnia, one in the Baltic proper and one in the Kattegat.

Thanks to Celsius and his imitators, scientists three generations later were able to solve the problem of whether the land was going up or the water going down. To start with, the Finnish-Swedish geodesist and cartographer Carl Peter Hällström (1823) published a table of rates of the water decrease at a number of sea level marks. It indicated that the highest rates were to be found in the Gulf of Bothnia and that the rates might be smaller further south, but the result was still somewhat inconclusive. Nevertheless, the Swedish chemist Jacob Berzelius (1830 & 1834) considered Hällström's table to speak in favour of a land uplift. He tried to explain a land uplift by applying a cooling and subsequent contraction of the Earth. This would force the crust to deform, causing it to rise in certain areas, at least in the Baltic Sea area.

In 1834 the leading English geologist Charles Lyell made a voyage to Sweden to study the remarkable phenomenon. Lyell (1835) describes how he originally questioned the possibility that a part of the Earth's surface could gradually rise out of the sea. Therefore he decided to go there to see for himself: ”The slow, constant, and insensible elevation of a large tract of land, is a process so different … that the fact appeared to require more than an ordinary weight of evidence for its confirmation.” Here he met Hällström and Berzelius and discussed the matter with them.

Lyell then went to Celsius' rock at the island of Lövgrund in the Gulf of Bothnia, to measure the height of his mean sea level mark. From a pilot there he got a personal estimate of the deviation of the instant sea level from the mean sea level. After correcting for this, he found that the mean sea level had become 2 feet 10 ½ inches lower than Celsius' mark in 103 years; see Figure 2-3. This yields a rate of change of 8.3 mm/yr. Lyell's value is only some 10 % larger than the value according to modern methods (Chapters 3 and 4). After that Lyell travelled to the Swedish south coast, in the southern part of the Baltic. From the appearances on the coast as well as the testimony of the inhabitants he concluded, quite correctly, that there was no change of relative level at all in that area.

Now the question of water decrease versus land uplift could be resolved. Going through the three possibilities given at the end of the last section we find:

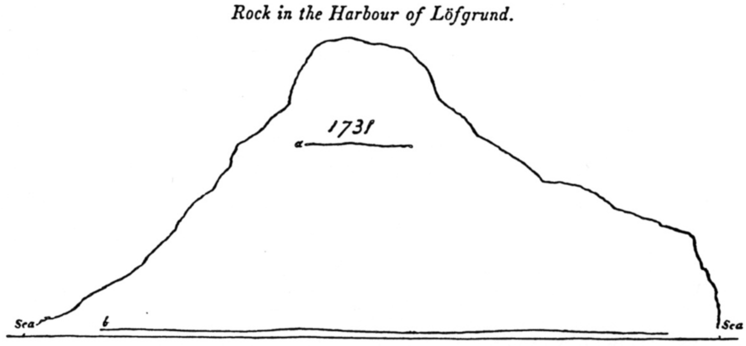


Figure 2-3. The Celsius rock at Lövgrund, with his mean sea level mark of 1731 (Lyell, 1835).

1. The observations contradict an equal rate of change in the whole Baltic Sea. Thus a general water decrease in the Baltic is ruled out.

2. 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.

3. The observations certainly 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.

Lyell (1835) concludes:

"In regard to the proposition, that the land in certain parts of Sweden is gradually rising, I have no hesitation in assenting to it after my visit. … I have no doubt that the rate of elevation is very different in different places. … I may be allowed to congratulate the scientific world that this wonderful phenomenon is every day exciting increased attention."

Concerning the origin of such a strange phenomenon, Lyell (1835a) found it difficult to explain but suggested that internal heating of the Earth could make the crust expand. This would cause a gradual rise of the crust in certain areas, at least in the Baltic Sea area.

Looking back for a moment we may note a fascinating mixture of contradictory hypotheses to explain what was going on in and around the Baltic Sea. We find one and the same cause explaining two opposite views: Frisi claimed that a cooling and contraction of the Earth would cause a water decrease; Berzelius claims that the same cooling and contraction of the Earth will cause a land uplift! We also find two opposite phenomena explaining one and the same thing: 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! It seemed as if the origin of the phenomenon could not be understood until a deeper insight into the temperature history of the Earth had been achieved. Moreover, to compare theory and observations one would have to get a better picture of the geographical distribution of the land uplift rates, in order to reveal a possible pattern in them.

2.4 The first land uplift map – one that was never constructed

By the time of Berzelius and Lyell there were quite many sea level marks along the Swedish and Finnish coasts of the Baltic. However, there was never any successful attempt made to establish a pattern of the land uplift rates, i.e. to construct a land uplift map, at that time. Was it not possible to do so from the data available? We will investigate this, trying to construct a land uplift map from the sea level data available around 1840, about 100 years after the first sea level marks were cut.

Many of the existing sea level marks around 1840 were relatively young and are, therefore, not old enough for our purpose. We will confine ourselves to marks established already in the 1700s to create a sufficiently long time span. Moreover, several of the reported sea level determinations were made under uncertain conditions or stem from anonymous people. We will confine ourselves to what we consider reasonably reliable data from known persons (most of them geodesists and hydrographers).

Altogether, this leaves us with 8 useful sea level marks. For each mark there are two useful sea level determinations, one at each end of a time span of about 50 – 100 years. In addition we have data from one sea level gauge with half a century of weekly observations (Stockholm). In total we thus have 9 sea level stations, six in Sweden and three in Finland;

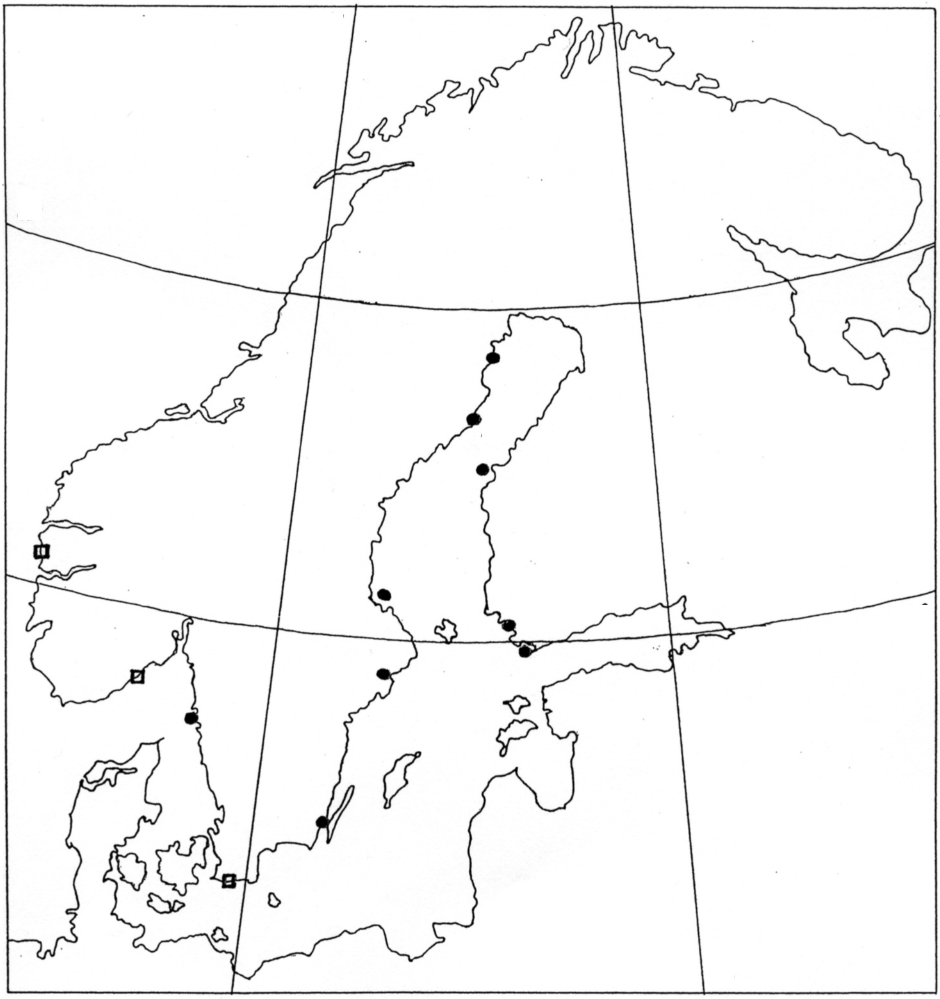


Figure 2-4. Sea level stations, mainly sea level marks, used for Table 2-1, denoted by black dots. Coasts with other sea level information indicated by squares.

see Figure 2-4 and Table 2-1. The Swedish data are mainly to be found in the above-mentioned papers by Hällström (1823) and Lyell (1835), while the Finnish data are mainly due to Hällström's brother, the Finnish physicist Gustaf Gabriel Hällström (1842).

The calculation of the land uplift values is quite straight-forward; the results are given in Table 2-1. Studying the values we note that they form

Table 2-1. Land uplift rates at sea level marks and one sea level gauge for the approximate period 1750 – 1830 (mm/yr).

Station	Lat.	Long.	Years	Rate
Hangöudd	59.8	22.9	1754 / 1837	6.0
Åbo slott	60.4	22.2	1750 / 1841	5.7
Vargö	63.0	21.2	1755 / 1821	12.0
Storrebben	65.2	21.7	1750 / 1796	12.3
Ledskär	64.0	20.9	1749 / 1819	11.0
Lövgrund	60.8	17.4	1731 / 1834	8.3
Stockholm	59.3	18.1	1774 – 1837	5.0
Skallö	56.7	16.4	1756 / 1800	0.3
Marstrand	57.9	11.5	1770 / 1834	3.8

some kind of pattern. They tend to increase from south to north, from 0 mm/yr in the southern Baltic to 12 mm/yr in the northern Gulf of Bothnia. Thus, at first glance the uplift seems to be latitude-dependent. However, counted from the maximum area nearly all stations are situated more or less to the south. We need to know something about the land uplift also in another direction. Fortunately, there is some information of that kind.

The Norwegian geologist Baltzar Mathias Keilhau (1838) tried to investigate if there was a land uplift along the Norwegian coast of the same kind as along the Swedish and Finnish ones. There were no old mean sea level marks to use, but he interviewed a lot of people living along the coast and studied some phenomena in nature. He found that there were signs of a moderate land uplift at least along the eastern part of the Norwegian south coast, i.e. in the northern Skagerrak. On the other hand, there was hardly any sign of a land uplift along the Norwegian west coast. These somewhat vaguely stated results are important complements to the numerical results above. In addition Lyell (1835), using the same methods, found that there was no sign of an uplift along the Swedish south coast, as mentioned earlier.

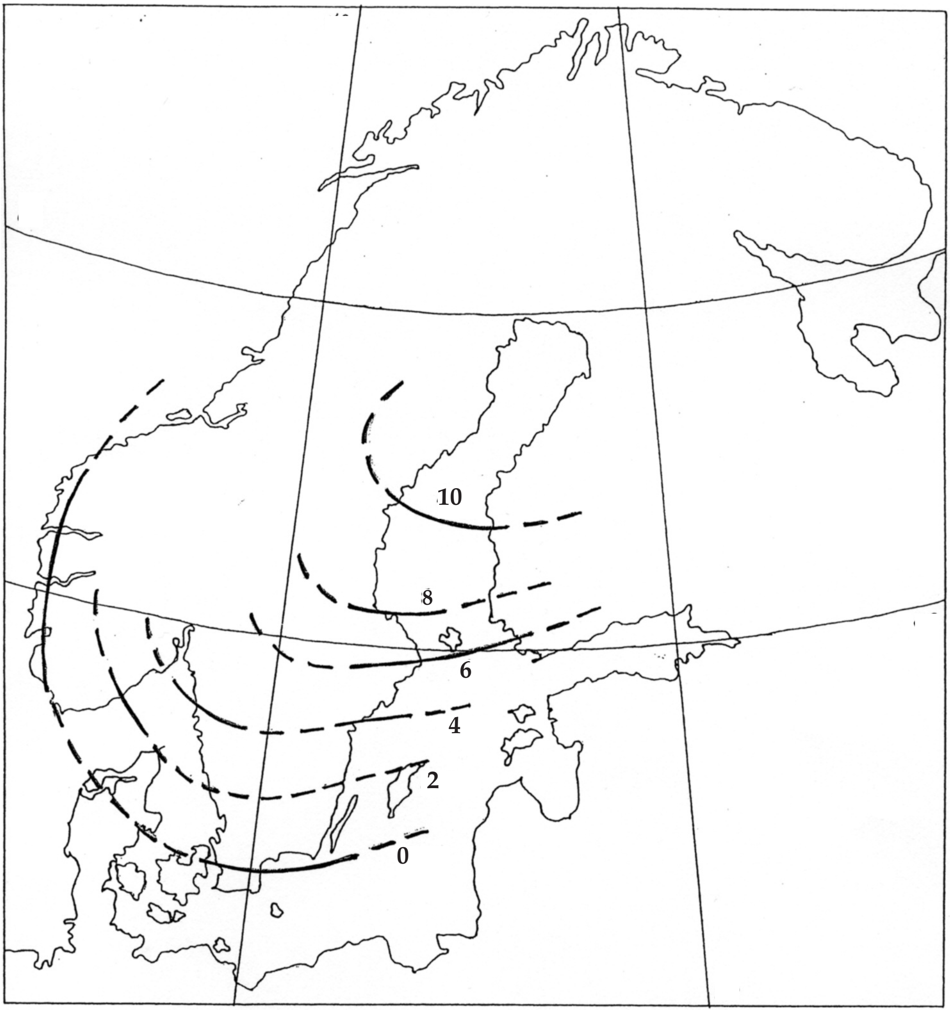


Figure 2-5. Land uplift map based on sea level data c. 1750 – c. 1830, mainly according to Table 2-1 (mm/yr).

We now are in the position to construct a land uplift map by drawing curves for every 2 mm/yr of uplift based on the data and information above. The result is presented in Figure 2-5. This is thus the very first land uplift map, based on data available in 1842. It reveals an interesting pattern. The map shows a phenomenon with a tendency of increasing uplift values from south as well as south-west and west towards the area around the northern half of the Gulf of Bothnia. In reality such a land uplift map was not constructed until more than 70 years later, as will be seen in the next chapter.

It is interesting to compare the land uplift map in Figure 2-5 with the corresponding modern map in Chapter 3 (Figure 3-5). The patterns agree quite well, but the uplift rates from the old sea level marks tend to exceed the modern rates by some 2 mm/yr. One reason for this is the fact that the modern rates represent the uplift of the crust relative to sea level during the 1900s. During this period sea level itself has risen by 1 mm/yr due to warmer climate, as discussed in Chapter 4. This climatic sea level rise did not occur during our period of approximately 1750 – 1830, making our rates systematically 1 mm/yr larger. A further reason might be the following. When the mean sea level marks were cut, mean sea level was in most cases probably estimated using peoples general impression of this level at their coast. Such an impression might be based on their integrated memories from the last two decades or so, yielding a mean sea level referring to a year about one decade earlier than the actual year of the mark. If the remeasurement 50 – 100 years later was less biased, an error in the uplift rate would occur, making the rates a further 1 mm/yr or so larger.

Why, then, was this land uplift map never constructed? The reason seems to be the peculiar meteorological variations in the level of the Baltic Sea, making the estimation of mean sea level problematic. Short-term sea level variations were easily visible and could be more or less averaged out (or perhaps corrected for). Long-term sea level variations, on the other hand, were not really understood at that time; they will be treated in detail in Chapter 5. Land uplift rates were calculated using all sorts of sea level marks and their sea level observations, without realizing the importance of selecting only those where the effects also of long-term sea level variations were minimized. Therefore, one could not find a clear pattern in the uplift rates obtained and, consequently, one could hardly find any basis for drawing a land uplift map. (A typical example of this is the inconclusive investigation of the Swedish geologist Leonard Holmström (1888) based on about 60 sea level marks.) The pattern of the land uplift map was hidden behind large amounts of unreliable data.

3. Postglacial rebound and the interior of the Earth

3.1 The discovery of the Ice Age

As we have seen in the last chapter, the thermal history of the Earth seemed to be important for finding the origin of the land uplift phenomenon. It would turn out that this was indeed the case, but in a completely different way than anticipated.

It started, a little preliminary, with a study by the Danish-Norwegian geologist Jens Esmark (1824). The mountain glaciers in Norway apparently were capable of transporting huge erratic blocks and building up long moraines. Esmark noted that erratic boulders as well as moraines could be found not only in the mountains, but almost over the whole of Norway. His conclusion was that Norway at some time must have been covered by ice.

Some years later the Swiss zoologist Louis Agassiz (1837) shocked his audience and readers by introducing an ice age into the history of the Earth. From the distribution of erratic boulders and moraines around the Alps he concluded that a large area there must have been covered by ice. But he extended his ideas to claim that a large part of Europe and the northern hemisphere had been glaciated during some period in the history of the Earth, the *Ice Age.* Lyell and most other Earth scientists of that time opposed this seemingly unlikely hypothesis.

Nevertheless, a complete *glaciation of the Nordic countries* was confirmed by investigations of the Swedish geologist and polar explorer Otto Torell (1859). He made scientific travels to both Iceland, Greenland and Spitsbergen. By comparing what he observed there with his findings in Sweden, Norway etc. he was able to show that the whole of the Nordic countries must have been covered by a thick ice. Furthermore, studying what he, correctly, considered was glacially striated bedrock, he found that the ice had expanded outwards from the Scandinavian mountain range over the whole Nordic and Baltic area.

The theory of the Ice Age was put into a framework of astronomically induced repeated ice ages by the French mathematician Joseph Adhémar (1842) and the British self-taught geophysicist James Croll (1875). They found a plausible explanation for the occurrence of ice ages in certain periodical variations related to the Earth as a celestial body: the variation in the direction in space of the Earth's rotational axis (the so-called precession), the variation in the obliquity of the Earth's orbit around the Sun, and the variation in the eccentricity of the Earth's orbit around the Sun. Together these would cause ice ages, or at least trigger them, with intervals of the order of 10 000 to 100 000 years.

We may note here that according to Adhémar a present growth of a large ice mass in the polar area of the southern hemisphere would cause the Earth's centre of gravity and, thereby, the sea water of the world to move southwards. Thus he tried in this way to reintroduce a latitude-dependent water decrease in the north. We have, however, already seen that this was hardly in agreement with the sea level observations there.

3.2 A new possibility: Postglacial uplift?

In 1865 a scientific paper was published in which the really interesting part is a short remark made at the end of one of the chapters. The author of the paper was the British geologist Thomas Jamieson. The remark contains a completely new idea concerning the land uplift. Based on the theory of the Ice Age, Jamieson (1865) writes as follows:

"It is worthy of remark that in Scandinavia and North America, as well as in Scotland, we have evidence of a depression of the land following close upon the presence of the great ice-covering; and, singular to say, the height to which marine fossils have been found in all these countries is very nearly the same. It has occurred to me that the enormous weight of ice thrown upon the land may have had something to do with this depression. Agassiz considers the ice to have been a mile thick in some parts of America; and everything points to a great thickness in Scandinavia and North Britain. We don't know what is the state of the matter on which the solid crust of the earth reposes. If it is in a state of fusion, a depression might take place from a cause of this kind, and then the melting of the ice would account for the rising of the land, which seems to have followed upon the decrease of the glaciers."

Here we have, for the first time, the hypothesis of what we now know as *postglacial rebound* or *postglacial land uplift*, sometimes referred to as *glacial isostatic adjustment*. Although only briefly formulated, it describes the phenomenon quite well. But did such a phenomenon really exist? Moreover, the remark points out a crucial question: What is the state of the matter beneath the crust? In other words: Is the Earth in general a solid or a fluid body? To all this, sea level observations of the Baltic Sea will turn out to provide interesting answers.

Jamieson's idea actually had a kind of forerunner. It had turned out that the observed gravitational attraction of the Himalayas was much less than calculated. It had then been suggested that this was due to the mountains being partly sunk into a yielding layer of higher density below. The crust should be in a state of equilibrium, later termed *isostatic equilibrium*.

However, Jamieson's idea was in general met with silence. One reason for this was that most geologists, although favouring a fluid Earth like Lyell (1835a), were still hesitant about the Ice Age. In any case, such a considerable and long-lasting reaction to a melting of the ice seemed too fantastic. Another reason was that geophysicists tended to favour a solid Earth. This was mainly due to a recent paper by the British physicist William Thomson (1863), later known as Lord Kelvin, in which he claimed that the tides of the world's oceans would be much smaller if the Earth itself behaved as a fluid. Later on Thomson's pupil, the British geophysicist George Howard Darwin (1882) presented an analysis of the so-called long-period tides, showing that the Earth, although being somewhat elastic, had a rigidity approximately equal to that of steel. The tidal results caused the German geographer Albrecht Penck (1882) to point out that Jamieson's postglacial rebound would be impossible because of the rigidity of the Earth.

After nearly two decades of almost no support for his idea, Jamieson (1882) returned to the subject in another paper. He emphasized that time was an important element in the problem: "Bodies that seem absolutely rigid to pressure applied for a short space of time yield perceptibly to a force which is long continued. … In regard to the pressure exerted by the ice, we must bear in mind that it probably continued for very many thousands of years." This still did not help very much for the moment. Even if some yielding could occur, was really the time elapsed enough to produce such a considerable phenomenon as the one observed? To most of his contemporaries this seemed extremely doubtful.

We should mention here that Penck instead of a postglacial land uplift suggested a regional water decrease, caused by a decreasing gravitational attraction from the ice due to its melting. This effect was so great, according to him, that it exceeded the rise of the water caused directly by the melting of the ice. However, by peforming mathematical calculations two other Germans, the meteorologist Hugo Hergesell (1887) and the geographer and polar explorer Erich von Drygalski (1887) were able to show that Penck had overestimated the effect by one order of magnitude. Moreover, it could not explain the still on-going change of level observed in the Baltic Sea.

So, in principle there were now three possibilities to explain the strange uplift phenomenon in the Baltic Sea area, leading to somewhat different uplift patterns:

1. Cooling and contraction of the Earth, as suggested by Berzelius. This would probably yield a somewhat irregular uplift pattern.

2. Heating and expansion of the Earth, as suggested by Lyell. This would probably yield a more smooth uplift pattern.

3. Postglacial rebound, as suggested by Jamieson. This would yield a fairly concentric uplift pattern over the formerly glaciated Nordic and Baltic area, with the highest uplift rates corresponding to the thickest ice somewhere in the centre.

3.3 Sea level gauges: Uplift rates and the marine limit

Obviously a map showing the geographical distribution of land uplift rates would be essential to solve the problem of the origin of the land uplift. A partial map of this kind, based on sea level data available already before the time of Jamieson, was presented in Chapter 2, Figure 2-5. Let us compare it with the three possibilities above:

1. The map, being quite regular, does not support a cooling and contraction of the Earth.

2. The map, although smooth, shows a geographical extension somewhat difficult to explain by a heating and expansion of the Earth.

3. The map, showing part of a concentric uplift pattern over the formerly glaciated area, clearly supports a *postglacial rebound*.

Unfortunately, as explained earlier, the map was never constructed at that time, because of lack of understanding of the peculiar long-term variations of the level of the Baltic Sea and their effects on the observations at the old sea level marks.

The sea level marks had the advantage of being fixed in the bedrock, but the disadvantage of not allowing daily readings of the sea level. By the middle of the 1800s one had realized the need for this and established a number of sea level scales along the Swedish and Finnish coasts, mostly located at light-houses and pilot stations. The basic method for calculating the land uplift rate from such a long series of daily sea level observations is the method of least squares applied to annual means of the sea level, in the form of linear regression. This method was first used by the Finnish-Swedish polar explorer Adolf Erik Nordenskiöld (1858), who applied it to the special sea level series of Stockholm, commencing already in 1774; see Figure 3-1.

The sea level scales had the advantage of allowing daily readings of the sea level, but the disadvantage of mostly not being fixed in the bedrock. Hence, many of them lacked the long-term stability needed for a reliable determination of the land uplift rate. (In the north there were also problems reading the sea level during winters because of thick ice.) Nevertheless, a few useful uplift rates were computed through linear regression by the climatologist Adolf Moberg (1873) for Finland and the hydrographer Lars Arvid Forssman (1876) for Sweden. These results confirmed the existence of the uplift, but they were insufficient for constructing a map of the uplift pattern.

Turning to a longer time perspective one could imagine using ancient shore-lines, i.e. raised beaches, for finding an uplift pattern. However, even if the height of such a shore-line could be measured, there were at that time still no means for determining the age of it.

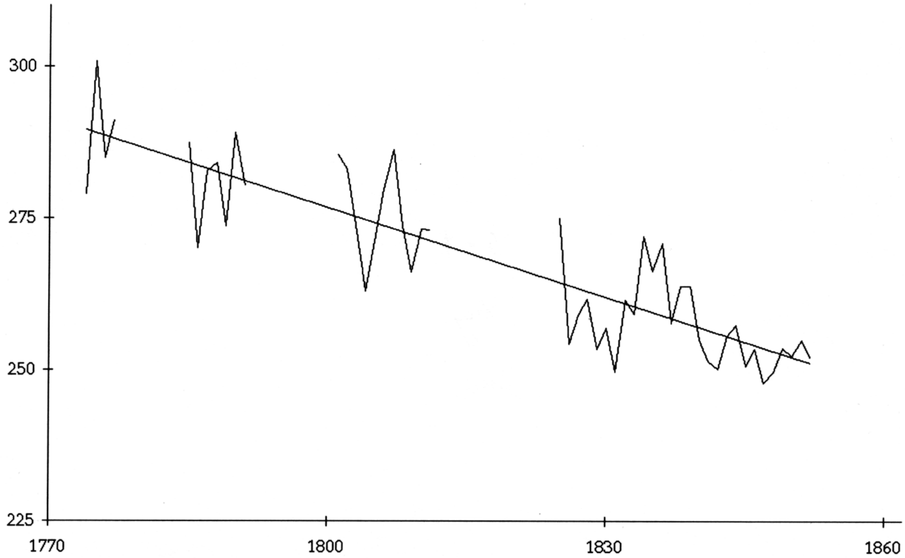


Figure 3-1. Land uplift determination through linear regression of annual mean sea levels (cm) at Stockholm for 1774 – 1852. (Recomputed from Nordenskiöld, 1858.)

So, the uplift pattern that was needed to determine the origin of the land uplift seemed to be difficult to reveal. What to do? Well, there was a method to circumvent the difficulties. The highest shore-line of all, known as the marine limit, was fairly easy to recognize at different locations within the uplift area. Although the age of it could not be determined, it might be assumed that it was of approximately the same age all over, namely from the end of the deglaciation. Thus it was sufficient to determine its height at as many locations as possible. This method was adopted by the Swedish geologist Gerard De Geer (1888 & 1890) to construct a land uplift map; see Figure 3-2.

De Geer notes from his map that the area of the land uplift coincides well with the area of the glaciation, and that the area of maximum uplift (over 200 m) coincides well with the area of maximum ice thickness. This leads De Geer (1888 & 1890) to his main conclusion:

"On the conditions mentioned it does, therefore, not seem to be easy avoiding the conclusion at which Jamieson arrived already in 1865, namely that the immense loading of the ice gradually caused a local de-

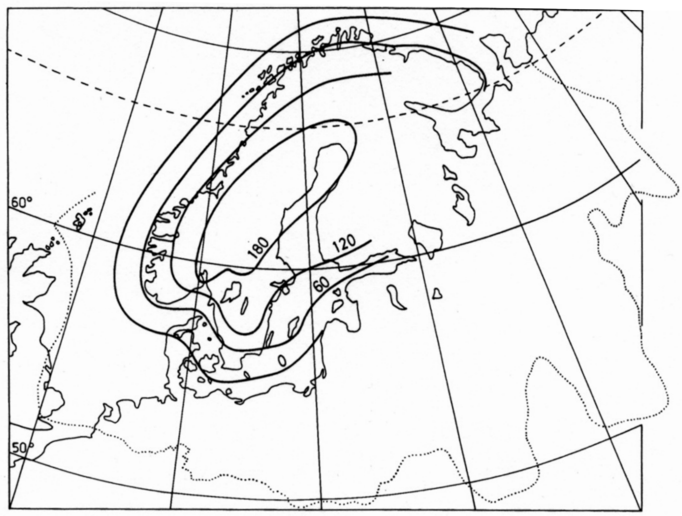


Figure 3-2. Land uplift map based on the height (m) of the marine limit. (Redrawn from De Geer, 1888.)

pression of the Earth's crust which is supposed to be in a fairly sensitive state of equilibrium, and that the area after the deglaciation slowly raised again although it has scarcely succeeded in fully reaching its original level."

Thus De Geer had succeeded in demonstrating that the strange phenomenon in the Baltic Sea area was, in fact, a *postglacial rebound* caused by the *unloading of the ice* having been present during the Ice Age. This was also in agreement with the findings of De Geer (1892) in eastern North America.

At about the same time De Geer embarked upon the time-consuming work of developing a method for dating raised beaches. The method was based on the existence of annual layers of clay, "varved clay", deposited below the marine limit. In principle each layer could be identified with a specific year, in a somewhat similar manner as for tree rings. In this way De Geer (1912) succeeded in establishing a geochronology for the last 12 000 years.

Applying this dating method, De Geer's pupil, the Swedish geotechnician Ragnar Lidén (1913), was able to construct a curve illustrating the land uplift as a function of time. This curve, based on data from the centre of the uplift area (Ångermanland), revealed that the uplift had been at least 10 times as rapid immediately after the melting of the ice. Furthermore, it revealed that the uplift since then has been decaying more or less exponentially. A complication when interpreting the data was caused by the rise of sea level itself due to the melting of the ice (the eustatic sea level rise), as discussed by the Irish geologist William Wright (1914) and the Finnish geologist Wilhelm Ramsay (1924).

By now the time also was ripe for constructing a (partial) map of the present land uplift, from uplift rates determined at sea level stations. Since the end of the 1800s a number of continuously recording sea level stations, mareographs, had been established along the coasts of the Baltic Sea. In a manner further described in Section 3.5, Blomqvist & Renqvist (1914) produced uplift rates and an uplift map for the Baltic Sea. This map of the ongoing uplift showed a pronounced similarity with the corresponding part of De Geer's map of the total uplift since the Ice Age.

3.4 The viscosity of the Earth's interior

The land uplift in the Baltic Sea area was now known to be a postglacial rebound. Moreover, uplift as a function of time as well as present uplift rates were determined with reasonable accuracy. This knowledge formed the basis of a much wider question: What is going on beneath the rising crust? In other words: What are the dynamical properties of the interior of the Earth – is it mainly an elastic solid or is it mainly a viscous fluid?

The question was initially taken up for discussion by the Norwegian oceanographer and polar explorer (and Nobel peace prize winner) Fridtjof Nansen (1921, 1927). He claimed that the uplift of the crust should be accompanied by a horizontal viscous inflow of subcrustal material; see Figure 3-3. This, in its turn, would also lead to a change in the gravity field in the uplift area.

The question was widened and put into a global context by the British geophysicist and geologist Arthur Holmes (1931). Two decades earlier Wegener's hypothesis of horizontally moving continents, continental drift, had been presented. It was, however, rejected or ignored by

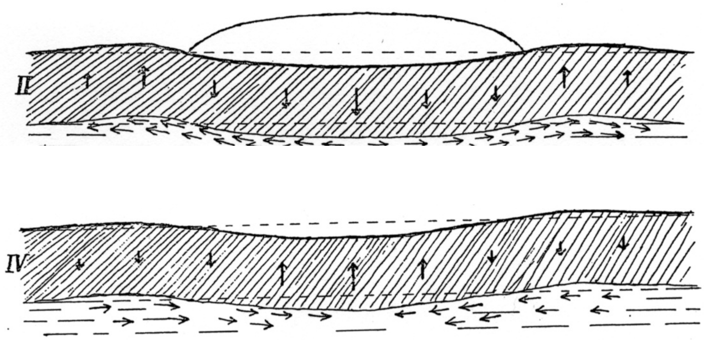


Figure 3-3. Changing ice load and viscous flow of subcrustal material (Nansen, 1921).

the vast majority of the scientists, mainly due to the lack of any known force mighty enough to produce such a motion of the continents. Now, Holmes suggested that convection currents, caused by radioactive heat, could be a driving force behind continental drift. For this to be possible, the Earth's interior had to be fluid enough, i.e. its viscosity had to be low enough. How should one be able to find out anything about the viscosity of the Earth's interior? From the postglacial rebound of Fennoscandia! According to Holmes, the uplift data indicated that the viscosity might be low enough to allow convection currents to exist inside the Earth.

The works of Nansen and Holmes inspired several authors to try to compute the *viscosity of the Earth's mantle*. Let us take a look at the basic theory for such computations. Suppose the ice sheet to be radially symmetric with radius r. Suppose further the mantle to be a fluid of uniform viscosity η and density ρ. Then the postglacial depression (remaining uplift) ΔH will decay as an exponential function of time t:

$$\Delta H = \Delta H_i \, e^{-\frac{g\rho r}{\pi\eta} t} \qquad (3\text{-}1)$$

Here ΔH_i denotes the initial depression (total uplift); g is the gravity acceleration. Differentiating this formula we obtain a relation between the present uplift rate $\dot{H}$ and the presently remaining uplift ΔH:

$$\frac{\dot{H}}{\Delta H} = \frac{g\rho r}{\pi\eta} \tag{3-2}$$

Hence, there are two possibilities to find the viscosity of the Earth's mantle from postglacial uplift data, one for each formula.

The first determination of the mantle viscosity was made by the Dutch geophysicist and geodesist Felix Andries Vening Meinesz (1934). Vening Meinesz had performed extensive gravity measurements at sea, thereby revealing patterns of gravity anomalies. He now suspected that these might be explained by the existence of convection currents in the mantle. Consequently, he was interested in trying to find a value for the viscosity of the mantle. Vening Meinesz applied formula (3-2). For the present uplift rate, from sea level records at the centre of the uplift around the Gulf of Bothnia, he used $\dot{H}$ = 1.0 cm/yr. The remaining uplift in the same area he tried to estimate from the pronounced negative gravity anomaly there; he used $\Delta H \approx 280$ m, later 180 m. Putting g = 9.8 m/s^2, knowing from seismology that ρ = 3.3 g/cm^3, and estimating from uplift data that r = 500 km, later 700 km, he then obtained

$$\eta \approx 4 \cdot 10^{21} \text{ Pas}$$

Although only a rough estimate, this was an epoch-making result. Its order of magnitude agrees well with modern values according to Section 3.6; the slight overestimation is mostly due to the uncertain method for finding the remaining uplift.

With the viscosity thus estimated from the present uplift rate combined with the remaining uplift, Vening Meinesz (1934) could also roughly estimate the speed of convection currents; he arrived at a possible speed of the order of cm/yr. Vening Meinesz concludes:

"In the opinion of the writer, there is every reason to admit the possibility of convection-currents in the Earth. ... It appears possible that the convection phenomenon can be responsible for important tectonic disturbances."

This comes close to an understanding of the mechanism behind continental drift (plate tectonics), one generation before the break-through for this theory.

The next year another determination of the mantle viscosity was made, by the American geophysicist Norman Haskell (1935). Haskell applied formula (3-1). He used the uplift curve from the centre of the uplift area (Ångermanland) as well as a curve from a more peripheral region to estimate the exponent in the formula. This led to a viscosity of $\eta = 10^{21}$ Pas. As can be seen this is in good agreement with the result from formula (3-2). Consequently, Vening Meinesz (1937) found reason to combine the two methods into one.

So, what about the old question whether the Earth in general is a solid or a fluid? We have two different answers depending on where the information comes from:

1. The Earth is an elastic solid. This is the information given from tidal phenomena.

2. The Earth is a viscous fluid. This is the information given from post-glacial rebound.

Which answer is the correct one? In this case the solution to the problem is very diplomatic:

1. The Earth behaves as an elastic solid when subject to forces of short duration – days, months, years.

2. The Earth behaves as a *viscous fluid* when subject to *forces of long duration* – thousands of years.

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.

The mantle viscosity now was known at least to its order of magnitude; this seemed to be an unambiguous result. Nevertheless, a result differing from that was published by Reinout Willem van Bemmelen & Hendrik Petrus Berlage (1934), two geophysicists working in the Dutch

East Indies (today's Indonesia). They had adopted a completely different approach to the problem, presupposing that viscous flow was confined to a thin layer (asthenosphere) immediately below the crust (lithosphere). The outcome was a viscosity two orders of magnitude lower. Haskell (1935) noted that by thickening their layer four times the viscosity would agree with his own theory. This indicated an ambiguity in the problem: Different Earth models with different layering might produce almost the same observed uplift. To perform a more accurate modelling of the Earth we would obviously require much more and better uplift data.

3.5 Mareographs: Mapping the uplift rate

In general, daily sea level observations in the Baltic Sea had started in connection with establishing a number of sea level gauges along its coasts. Along the Swedish and Finnish coasts sea level scales had been put up around 1850, along the German coast already around 1810. As mentioned earlier, however, only a limited number of the stations turned out to be reliable enough for determining land uplift rates.

Around 1890 a large number of continuously recording sea level gauges, mareographs, had been established in the Baltic Sea and adjacent waters. These were, if possible, placed on bedrock and, in any case, repeatedly controlled. They constituted a set of sea level stations reliable also for the determination of uplift rates. After a few decades the first maps of uplift rates based on data from both sea level scales and mareographs appeared.

When trying to calculate an uplift rate from annual sea level means in the Baltic there emerges a problem. What is observed in a series of annual mean sea levels is not only the phenomenon we want to study, the uplift, but also other phenomena, especially the peculiar long-term variations of the Baltic sea level itself. As these are more or less common to the Baltic as a whole (see Chapter 5), there are two principle possibilities to deal with this effect. One way would be to use the same time period for all sea level stations and, in case some station differs in time, reduce that one to the common time period by comparison with a neighbouring station. Another way would be to try to find relations between the sea level variations and the wind field (air pressure gradients) and thereby hopefully eliminate most of the atmospherically induced sea level variations.

The first (partial) map of land uplift rates based on data from sea level scales and mareographs in the Baltic was computed by Edvard Blomqvist & Henrik Renqvist (1914), Blomqvist being a Finnish geodesist and hydrologist and Renqvist being a Finnish oceanographer and seismologist. They used a common time period, including neighbour station reductions, to handle the influence from the sea level variations. This method works well and leads to a consistent set of uplift rates, making them comparable with each other. However, the ″absolute″ value of the uplift rate still becomes uncertain for time periods of only a few decades. An approximate way of handling that by studying the long time series of Stockholm was applied by the Swedish hydrographer Folke Bergsten (1930).

Later on an improved uplift map was published by the Finnish oceanographer (and foreign minister) Rolf Witting (1943). Witting used, to some extent, wind field reductions to handle the sea level variations. In addition, to be on the safe side, he used a common time period. The result was an uplift map that was not only consistent but also somewhat improved in the ″absolute″ sense.

As time went, the time series of the sea level stations became longer but also more different in time. Some old stations, mostly sea level scales, were closed down while new ones, mostly mareographs, were added. It became increasingly tempting to use all available sea level data, irrespective of their differing time periods, and also data from outside the Baltic. This was made by the German-American geophysicist and seismologist Beno Gutenberg (1941), without atmospheric reductions, and, with some reductions for air pressure, by the British oceanographer Jack Rossiter (1967). It only led to limited improvements.

In order to fully utilize the sea level data of the Baltic Sea area for calculating reliable land uplift rates, there are several things to consider. Let us take a look at the situation as a whole. There are now more than 50 sea level stations that have reliable records spanning at least 60 years; no less than half of them have records of about 100 years. The records span considerably different time periods with, in some cases, only little overlapping between neighbouring stations; there are even cases where neighbouring stations do not have any common years at all. Hence, it is not possible to use a common time period, not even through neighbour station reductions. Neither is it possible to make atmospheric reductions for all the time periods, because of lack of good atmospheric data for the older years.

Now, in the annual sea level data there are two phenomena recorded, the effects of which are essential to eliminate from the land uplift determination. One has already been pointed out above; it is the special long-term wind-driven sea level variations of the Baltic (see further Chapter 5). The other one is the increase in global sea level rise due to warmer climate with melting glaciers etc. (see further Chapter 4). What to do?

Both these effects, being common to the Baltic Sea as a whole, can be successfully handled by modifying the method of Blomqvist & Renqvist, taking advantage of the extremely long sea level series of Stockholm. The *Stockholm sea level series*, commencing in 1774, covers the years of all the other sea level stations, whatever time period they might have. Moreover, its position in the central part of the Baltic Sea, where disturbing short-term sea level variations have a minimum (see Chapter 5), makes it well suited for comparisons with other stations. Hence, the uplift rate of a station with an arbitrary time period can be reduced to a specified time period by comparing the years of the station with exactly the same years at Stockholm. That gives the difference in uplift rate, and then adding the uplift rate of Stockholm for the specified time period gives the uplift rate of the station for the same time period. In this way the uplift rates of all stations can be reduced to a common time period. This requires that the whole Stockholm series is reliable and accurate enough; this is indeed the case as shown by the author (Ekman, 2003), who has recomputed it based on the original documents (see also Section 1.3 and Appendix).

With the above method the author has computed land uplift rates for 56 reliable sea level stations, all reduced to a common 100-year-period, 1892 – 1991; see Ekman (1996). Stockholm was used as the main reference station, valid for all stations within the Baltic Sea; for stations outside the Baltic, where sea level is somewhat less correlated with Stockholm, a station in the Skagerrak (Smögen) was used. All stations with their years and final uplift rates are listed in Table 3-1, this being a complete set of uplift rates forming a consistent system; see also Figure 3-4.

Table 3-1. Apparent land uplift rates at sea level stations reduced to the 100-year-period 1892 – 1991 (mm/yr). Stations are in anti-clockwise order around the Baltic (grouped by countries).

Station	Lat.	Long.	Years	Rate
Kronstadt	59 59	29 47	1841 – 1916	0.09
Hamina	60 34	27 11	1929 –	1.67
Helsinki	60 09	24 58	1904 –	2.28
Hanko	59 49	22 58	1888 –	2.99
Turku	60 25	22 06	1922 –	4.05
Degerby (Åland)	60 02	20 23	1924 –	4.11
Lemström (Åland)	60 06	20 01	1889 –	4.57
Lypyrtti	60 36	21 14	1858 – 1922	5.06
Rauma	61 08	21 29	1933 –	5.22
Mäntyluoto	61 36	21 29	1913 –	6.31
Kaskinen	62 23	21 13	1927 –	7.11
Vaasa	63 06	21 34	1913 –	7.62
Pietarsaari	63 42	22 42	1915 –	8.04
Raahe	64 42	24 30	1923 – 1975	7.54
Oulu	65 02	25 26	1913 –	6.66
Kemi	65 44	24 33	1920 – 1976	7.14
Furuögrund	64 55	21 14	1916 –	8.75
Ratan	64 00	20 55	1892 –	8.16
Draghällan	62 20	17 28	1898 –	7.57
Gävle	60 41	17 10	1896 –	5.90
Björn	60 38	17 58	1892 – 1976	5.95
Stockholm	59 19	18 05	1774 –	3.98
Grönskär	59 16	19 02	1849 – 1930	3.97
Södertälje	59 12	17 38	1869 – 1969	3.66
Landsort	58 45	17 52	1887 –	3.06
Visby (Gotland)	57 39	18 18	1916 –	1.45
Ölands norra udde	57 22	17 06	1887 –	1.29
Kungsholmsfort	56 06	15 35	1887 –	0.20
Ystad	55 25	13 49	1887 – 1986	- 0.62
Klagshamn	55 31	12 55	1930 –	- 0.04

Varberg	57 06	12 13	1887 – 1981	0.77
Smögen	58 22	11 13	1895 –	1.99
Oslo	59 54	10 45	1914 –	4.10
(Nevlunghavn	58 58	9 53	1927 – 1965	1.56)
Tregde	58 00	7 34	1928 –	- 0.05
Stavanger	58 58	5 44	1914 –	- 0.19
Bergen	60 24	5 18	1883 –	0.24
Heimsjø	63 26	9 04	1928 –	1.47
Narvik	68 26	17 25	1906 –	3.06
(Vardø	70 20	31 06	1880 – 1965	0.81)
Esbjerg	55 28	8 27	1889 –	- 1.04
Hirtshals	57 36	9 57	1891 –	0.38
Frederikshavn	57 26	10 34	1893 –	0.49
Århus	56 09	10 13	1889 –	- 0.49
Fredericia	55 34	9 46	1890 –	- 0.96
Slipshavn	55 17	10 50	1890 –	- 0.83
Korsør	55 20	11 08	1890 –	- 0.61
Hornbæk	56 06	12 28	1891 –	- 0.08
København	55 41	12 36	1889 –	- 0.24
Gedser	54 34	11 58	1892 –	- 0.94
Marienleuchte	54 30	11 15	1882 – 1944	- 0.72
Travemünde	53 58	10 52	1855 –	- 1.80
Wismar	53 54	11 28	1849 –	- 1.31
Warnemünde	54 11	12 05	1856 –	- 1.06
Swinemünde	53 55	14 16	1811 –	- 0.77
Kolberg	54 11	15 34	1825 – 1935	- 0.95
Pillau	54 39	19 54	1816 – 1944	- 1.22
Liepaja	56 32	20 59	1865 – 1936	- 0.30

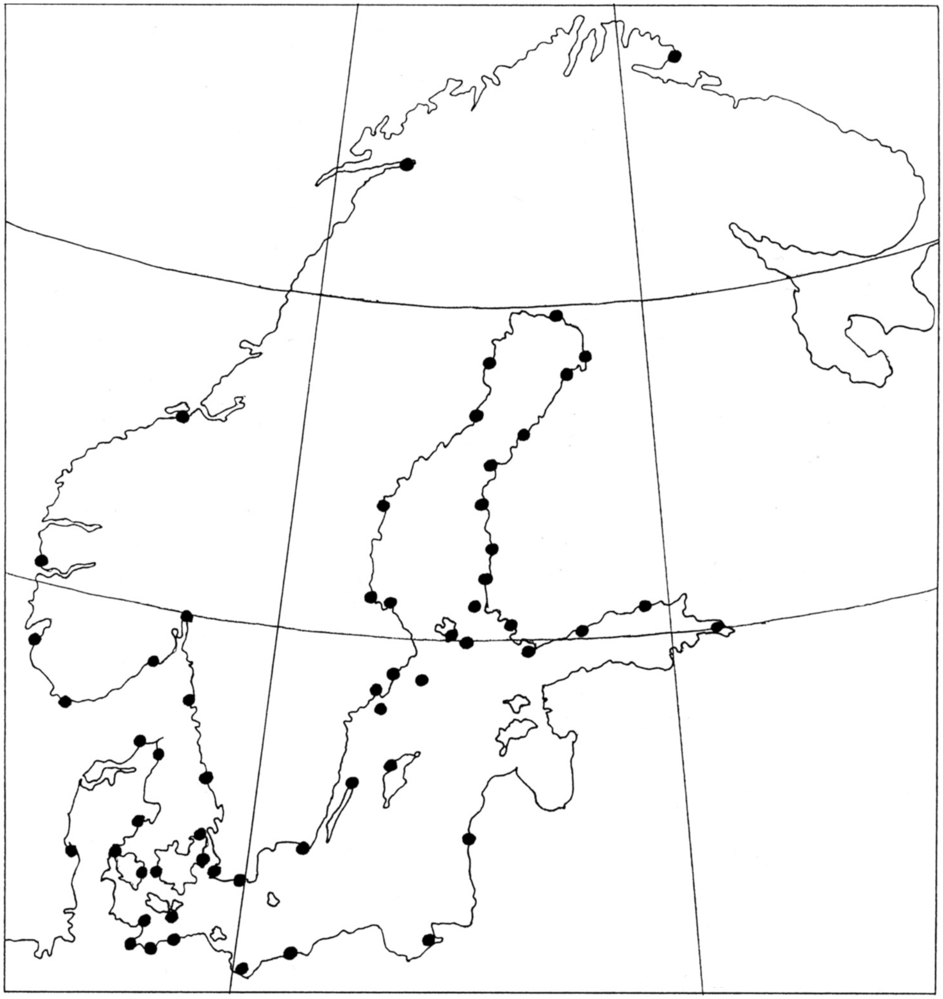


Figure 3-4. Sea level stations in the Baltic Sea and adjacent waters listed in Table 3-1.

The standard errors of the uplift rates are typically around 0.20 mm/yr. They exhibit a geographical pattern related to the behaviour of the long-term sea level variations, with minimum values (0.08 mm/yr) at the Baltic entrance, and maximum values (0.24 mm/yr) in the inner parts of the Gulf of Bothnia and the Gulf of Finland; see further Ekman (1996) and Chapter 5 (Table 5-2).

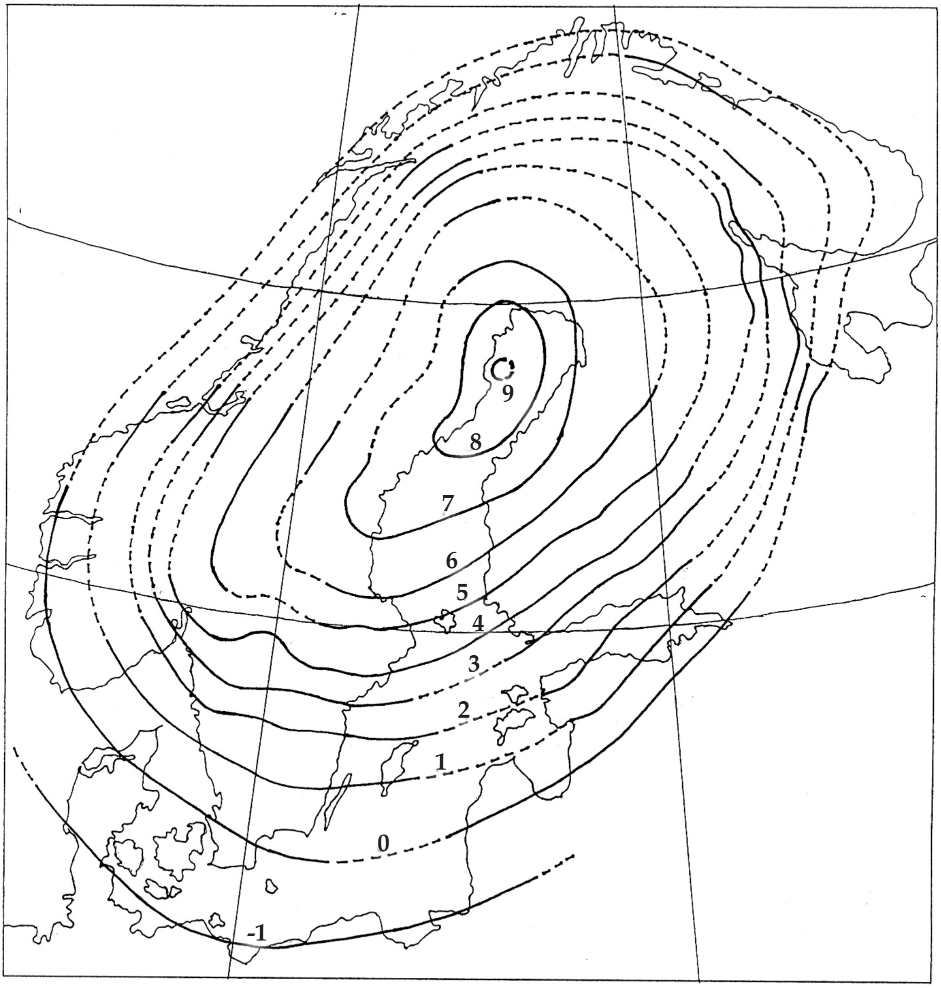


Figure 3-5. Map of apparent postglacial land uplift for the 100-year-period 1892 – 1991 (mm/yr), based mainly on Table 3-1 (Ekman, 1996).

The accompanying land uplift map is shown in Figure 3-5. The uplift rates of Table 3-1 form the consistent basis of the map. The inland parts rely to a varying degree also on some lake level recordings and, although somewhat less accurate, on repeated national levellings, the first levelling contributions coming from the Finnish geodesist Erkki Kääriäinen (1953).

The uplift rates of Table 3-1 (and Figure 3-5) represent the *apparent land uplift*, $\dot{H}_a$, i.e. the uplift of the crust relative to the mean sea level, during the period 1892 – 1991. During the same period the mild climate with melting glaciers has caused a global *climatic rise in mean sea level* itself, sometimes known as the *eustatic rise*, $\dot{z}$. Moreover, the viscous inflow of mass below the uplifted crust causes an increase in gravity leading to a *gravitational rise in mean sea level*, known as the *geoid rise*, $\dot{N}$, in the Baltic. Adding these effects we obtain the rate of the *absolute land uplift*:

$$\dot{h} = \dot{H}_a + \dot{z} + \dot{N} \tag{3-3}$$

The maximum of the quantity $\dot{H}_a$ can, according to above, be put to 9.0 mm/yr. The quantity $\dot{z}$ turns out to be about 1.0 mm/yr; it is treated in Chapter 4. The maximum of the quantity $\dot{N}$ can be shown to be about 0.6 mm/yr; see below. Summing the three quantities we obtain the maximum absolute land uplift rate,

$$\dot{h}_0 = 9.0 + 1.0 + 0.6 = 10.6 \text{ mm/yr}$$

The gravitational rise in mean sea level, 0.6 mm/yr, may be computed with sufficient accuracy by approximating the shape of the land uplift with a cosine surface of radius r and central "height" $\dot{h}_0$, and then integrating:

$$\dot{N}_0 = \frac{2\pi G\rho}{g} \int_0^r \dot{h}_0 \cos ks \, ds \tag{3-4}$$

(For the other symbols see Section 3.4.) Performing the integration (with $k = \pi/2r$) we obtain

$$\dot{N}_0 = \frac{4G\rho r}{g} \dot{h}_0 = 0.90 \cdot 10^{-4} \, r\dot{h}_0 \tag{3-5}$$

Since $\dot{h}_0$ through (3-3) already requires knowledge of $\dot{N}_0$, (3-5) and (3-3) have to be computed iteratively, starting by putting $\dot{N}_0$ to zero in (3-3). This method was used by the author and his Finnish colleague Jaakko Mäkinen (Ekman & Mäkinen, 1996) to find the numerical value of the gravitational sea level rise given above.

Finally a special remark should be made. Before about 1890 global mean sea level was not rising, due to generally colder climate at that time (Chapter 4). In addition, since about 1990 winters in northern Europe have been dominated by persistent westerly winds, leading to a higher mean sea level in the Baltic Sea (Chapter 5). Thus the 100-year-period 1892 – 1991 used here is an oceanographically very favourable period for the linear calculation of uplift rates; it can hardly be changed very much without causing interpretation problems.

3.6 Modelling the mantle, crust and ice of the Earth

When determining the viscosity of the Earth's interior from land uplift data one had, as discussed in Section 3.4, mostly worked with a homogeneous mantle. For a long time it seemed too complicated to handle Earth models with layers of different viscosities. However, the Canadian geophysicist Robert McConnell (1965) succeeded in developing a post-glacial rebound theory for a layered Earth, a generalization of the earlier theory. McConnell used an Earth with a *lower mantle*, an *upper mantle* and, on the surface, a *lithosphere (crust)*. The existence of a lower and an upper mantle is known from seismology. Putting data from the Fennoscandian uplift into his formulae allowed the determination of a viscosity for the lower mantle, another viscosity for the upper mantle and, in addition to that, a thickness of the lithosphere. A little later another Canadian geophysicist, Richard Peltier (1974), as a start of a long series of investigations, also developed a multi-layer theory, but with a different approach.

The time when McConnell presented his work was precisely the time of break-through for the theory of continental drift (plate tectonics). McConnell pointed out the importance of studying the viscosity structure of the Earth through the Fennoscandian uplift in order to understand the process of continental drift.

A characteristic problem with a layered Earth is the ambiguity in any solution that is not founded on a very large amount of data. A first example of that was mentioned earlier in connection with Haskell's discussion of the thickness of a possible low-viscosity channel in the uppermost mantle, an asthenosphere. After McConnell had introduced a layered Earth another ambiguity involving the asthenosphere was investigated by the German geophysicist Detlef Wolf (1986). He showed that exponential uplift curves and present uplift rates from the centre of the rebound area allowed two different solutions: a thick lithosphere and no low-viscosity asthenosphere at all as well as a thinner lithosphere and a low-viscosity asthenosphere.

Relying more extensively on present uplift rates, the Norwegian geophysicist Willy Fjeldskaar and his American colleague Lawrence Cathles (1991) concentrated on investigating the existence of a low-viscosity asthenosphere. They concluded that the pattern of uplift rates, especially the maximum value, was not possible to explain without introducing a low-viscosity asthenosphere.

Hitherto, however, the attempts to resolve the structure of the Earth were hampered by only using subsets of all available uplift data. Moreover, the investigations were performed using relatively simple models of the ice load, whereas taking advantage of all the uplift data might give the possibility to develop a more realistic ice model. This, in its turn, would also improve the Earth model.

These problems were now attacked in two consecutive investigations by the Australian geophysicist Kurt Lambeck and his colleagues. In the first investigation, by Kurt Lambeck, Catherine Smither & Paul Johnston (1998), a comprehensive geological data base for uplift curves in Fennoscandia and its surroundings was compiled. The optimum solution for a three-layered Earth (lower mantle, upper mantle, lithosphere), and an asymmetric ice cover on top of that, was searched for. The result was $\eta_{lm} = 0.8 \cdot 10^{22}$ Pas, $\eta_{um} = 0.4 \cdot 10^{21}$ Pas, and $D_l = 75$ km, for the lower mantle viscosity, the upper mantle viscosity, and the thickness of the lithosphere, respectively.

In the other investigation, by Lambeck, Smither & Ekman (1998), the consistent set of uplift rates from the sea level stations of the Baltic Sea and its surrounding waters, presented in Section 3.5 (Ekman, 1996), was used. Again, the optimum solution for a three-layered Earth with an asymmetric ice cover was searched for. The result in this case was

$\eta_{lm} = 2 \cdot 10^{22}$ Pas
$\eta_{um} = 0.5 \cdot 10^{21}$ Pas
$D_l = 110$ km

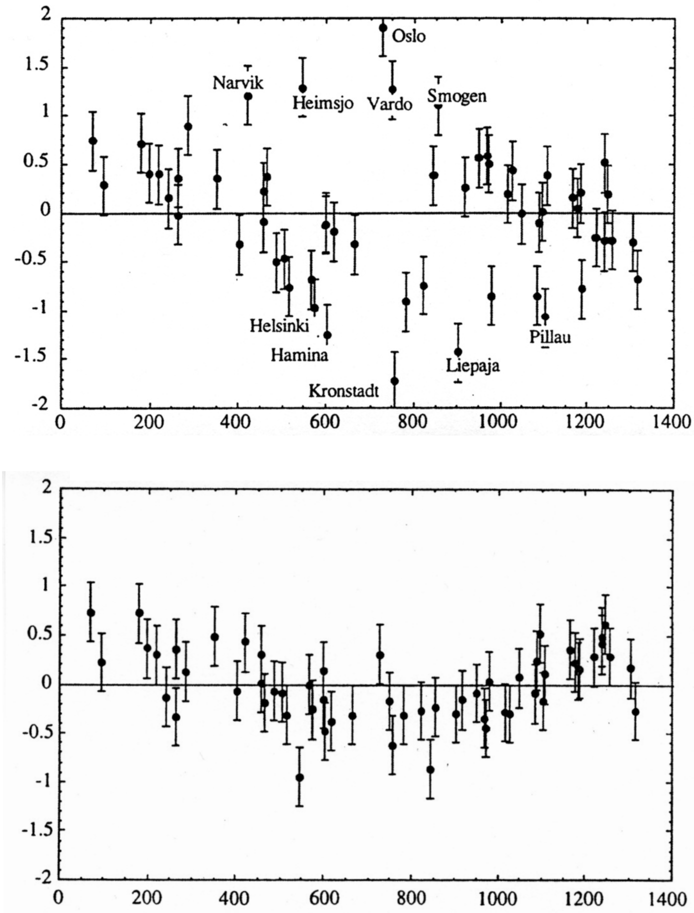


Figure 3-6. Observed minus predicted uplift rates (mm/yr) versus distance from centre of rebound (km), for a symmetric ice sheet (above) and for an asymmetric ice sheet (below) (Lambeck at al, 1998).

The two solutions agree well; the discrepancies between them are within the confidence limits for all the three quantities in the Earth model.

The solution for the ice model is the same in both cases. The resultant model is an *asymmetric ice sheet* with a maximum thickness of 2000 m. It is instructive to compare the predicted uplift rates for two different ice models, one symmetric and one asymmetric, with the observed uplift rates, i.e. with the rates calculated from the sea level stations according to Section 3.5. We refer to Figure 3-6.

The upper diagram in Figure 3-6 shows the discrepancies between observed and predicted uplift rates for an ice sheet with a symmetric and more or less parabolic profile. Many of the discrepancies are much too large in relation to the standard errors of the observed uplift rates, here illustrated by their upper limit of 0.3 mm/yr. Furthermore, these discrepancies are systematically positive in the north-west and negative in the south-east. This cannot reasonably be explained by errors in the Earth model; it implies considerable defects in the ice model.

The lower diagram in Figure 3-6 shows the discrepancies between observed and predicted uplift rates for the present solution with an ice sheet having an asymmetric profile. The asymmetry could, according to Lambeck et al (1998), be due to the ice probably resting on frozen ground along the mountain range in the north-west and on unfrozen ground in the south-east. Here the fit between model and observations is excellent; only a slight systematic effect remains.

What, then, about the asthenosphere? Introducing such a further layer in the above Earth model is apparently not needed in order to obtain a good agreement between model and observations. Still adding it would diminish the resolving power of the analysis.

On the whole, the above modelling of the postglacial rebound shows that sea level data from the Baltic Sea are of great importance for studying the interior of the Earth, and that they contain a lot of information on the ice sheet that disappeared 10 000 years ago. As an important by-product, the modelling also allows a determination of the present climatic rise of sea level. That will be discussed in Chapter 4. Some visible consequences of the viscous rebound of the Earth are shown in Figures 3-7 and 3-8.

Finally we should note the new possibility to determine (absolute) uplift rates through continuous satellite positioning. This method has been developed during the last decades, and recently been successfully applied to the Fennoscandian uplift by a Swedish-American group of geodesists, Martin Lidberg, Jan Johansson, Hans-Georg Scherneck and Jim Davis (2007). This is, strictly speaking, outside the scope of the book, but in combination with sea level observations it will also allow estimating the climatic rise of sea level (in Chapter 4).

Figure 3-7. Ancient boulder shore that is situated high above sea level because of the postglacial rebound (northern part of the Åland Islands).

Figure 3-8. Old boat house that is no longer possible to reach by boat because of the postglacial rebound (close to the Celsius rock at Lövgrund).

4. Climatic sea level rise and the glaciers

4.1 The water level at the sluice: A change in the rate of change?

As stated earlier, systematic sea level observations started in Stockholm already in 1774. These observations were made at the sluice (with lock gates) between the Baltic Sea, east of Stockholm, and Lake Mälaren, west of Stockholm; see Figure 4-1. When more than 100 years of data had been collected at the Stockholm sluice, they were analysed by the Swedish sluice and water engineer Victor Edvard Lilienberg (1891).

Lilienberg made a comprehensive study of all sorts of data from the Stockholm sluice, based on earlier compilations as well as original documents. Although a large number of errors and misinterpretations have slipped into his tables, his main conclusions hold. Lilienberg, when dealing with the series of annual mean sea levels from the sluice, noticed that the land uplift rate calculated from these data to some extent depended on the time period used for the calculation. The method of least squares applied to the annual means showed a slight tendency of giving larger uplift rates for earlier time periods and smaller uplift rates for later time periods. Lilienberg (1891) writes:

”Using this method of calculation one soon realizes that different time periods yield different results concerning the secular decrease of water. … The water level does not seem to have lowered according to a straight line, but according to a curve or an arc.”

He does not comment upon this any further; he merely states that the normal sea level at any instant, as well as its rate of change at the same instant, can be obtained from the curve he has constructed.

Lilienberg thus had started a search for a possible change in the rate of change of the sea level, and even found a weak indication of such a change in the rate of change. This might be regarded as a first indication of what we today know as the *climatic (global) sea level rise*, or the *eustatic sea level rise*, due to global warming. This climatic sea level rise, starting

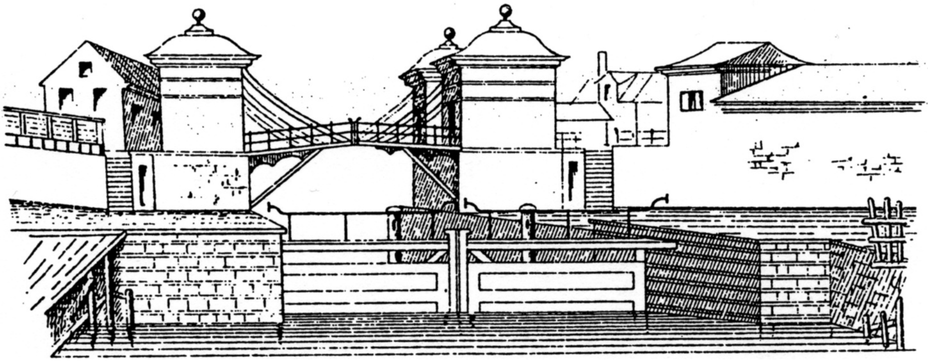


Figure 4-1. The Stockholm sluice around 1780 (Lilienberg, 1891).

in the second half of the 1800s, will conceal a part of the land uplift going on in the Baltic Sea; it could thus explain the observations at the Stockholm sluice, but they could also be explained by other effects.

A generation later, the Swedish hydrographer Folke Bergsten (1930) still noticed the same thing as Lilienberg in the Stockholm sea level data. Bergsten ascribed it loosely to meteorological causes.

The phenomenon in the Stockholm sea level data could in principle be looked upon in two different ways:

1. A special phenomenon affecting the Baltic Sea, due to some regional meteorological change.

2. A general phenomenon affecting the world ocean, due to some global climatic change.

4.2 Melting glaciers and sea level rise

During the 1930s the Icelandic glaciologist and vulcanologist Sigurður Thorarinsson studied the changes in volume of the main Icelandic glacier Vatnajökull. He arrived at the conclusion that it had diminished since at least 1890. This was in accordance with results of similar studies of other glaciers in the world.

However, Thorarinsson (1940) went one step further. He wished to estimate if the melting of glaciers had any impact on global sea level. To do so he compiled data on the diminishing of the geographical extension of glaciers all over the world from a large number of sources. In addition he compiled data on the thinning of glaciers. From this he could estimate the loss in glacier volume, and then turn it into a corresponding rise in global sea level. Thorarinsson (1940) concludes:

”The ice-thinning in the last few decades of the world's glacier districts, exclusive of the whole Antarctis and the accumulation area of the Greenland ice, has thus – ceteris paribus – resulted in the ocean levels being raised eustatically about 0.05 cm per annum.”

This is the first estimate of the global rise of sea level due to a warmer climate. Thorarinsson's figure of 0.5 mm/yr, although very approximate according to himself, is of the right order of magnitude according to modern estimates (see Section 4.3).

Thorarinsson found a support for his result in the sea level studies based on the data of the Stockholm sluice:

”From about 1850 the smoothed Stockholm curve also shows a tendency towards flattening, and that tendency has been more marked since about 1890. There is certainly nothing unreasonable in associating this with the glacier shrinkage that began about the middle of the 1800s.”

Moreover, the Stockholm data did not allow a considerably larger global rise of the sea level than that which Thorarinsson had estimated. This led him to the conclusion that the extensive ice covers of Antarctica and Greenland did not experience any significant melting.

Independently of Thorarinsson, the German-American geophysicist and seismologist Beno Gutenberg (1941) worked on the same sea level problem, but from a different point of view. He computed rates of change of the sea level for mareographs all over the world, in this context excluding the Baltic Sea with its postglacial land uplift. The global average of all rates, for approximately the first half of the 1900s, turned out to be a rise in sea level of 1.1 mm/yr, although with a large standard error.

Returning to the early observations of a change in the Stockholm sea level trend, it is now possible to choose between the two different views presented at the end of the last section:

1. The phenomenon can hardly be a regional one restricted to the Baltic Sea.

2. The phenomenon is most probably a global one, a recently started *climatic sea level rise* associated with *melting of the world's mountain glaciers*.

A similar effect as had been observed in Stockholm, i.e. a change in the sea level trend, could later also be found in the few other extremely long sea level series existing in the world, all of them in northern Europe. It was found in Amsterdam at the North Sea coast by the Dutch coastal engineer Johan van Veen (1945). It was also found in Brest at the Atlantic coast (as well as in Swinemünde at the southern Baltic Sea coast) by the Finnish oceanographer Eugenie Lisitzin (1958). Thus the results from different seas, although uncertain, pointed in the same direction.

An additional piece of information useful in this context was the present rate of land uplift or land subsidence that could be estimated (extrapolated) from ancient shore-line data. Subtracting this rate from the observed sea level trend would yield an estimate of the rate of the sea level rise. This method was applied for Amsterdam by the Australian geologist and geophysicist Rhodes Fairbridge (1961) and for Stockholm (together with Amsterdam) by the Swedish geologist Nils-Axel Mörner (1973), leading to a sea level rise close to 1.0 mm/yr.

4.3 Sea level rise and global warming

The *rate of the climatic sea level rise* is a very important quantity, reflecting global warming, but also a very small quantity, one order of magnitude smaller than the maximum rate of the postglacial land uplift. Therefore it is difficult to determine with sufficient accuracy. In fact, none of the determinations in the preceding sections had been shown to be significantly different from zero. Thus it would be essential to find out to what extent the observed quantities really are statistically significant. This could be achieved by awaiting longer time series in combination with improving the methods of analysis. Also in order to minimize the disturbing influence from the wind-induced long-term sea level variations of the Baltic (Chapter 5), very long time series are needed.

The Stockholm sea level series, by now the longest continued one in the world, has been analysed by the author (Ekman, 1988). After recomputation of the annual mean sea levels, taking neglected historical information and data into account, the whole series of annual mean sea levels was divided into two parts of about 100 years each. By linear regression the rate of apparent land uplift was found to be 4.93 ± 0.23 mm/yr for the years 1774 – 1884 and 3.92 ± 0.19 mm/yr for the years 1885 – 1984; see also Figure 4-2. From this an increase in the rate of the climatic sea level rise amounting to

$$\Delta \dot{z} = 1.01 \pm 0.30 \text{ mm/yr}$$

was obtained. This could be shown by a t-test to be highly statistically significant, at the 99.9 % level.

One might argue here that there could be regional Baltic factors on a secular time scale influencing the result. Possible such factors for most of the past century would be increasing south-westerly winds over the Baltic entrance and increasing salinity in the Baltic Sea. However, their effects on sea level change can be shown to be very small; moreover, they partly cancel each other since the effect of the winds is a higher sea level and that of the salinity a lower one.

The Stockholm result inspired to a search for a significant sea level ”acceleration” also for the other extremely long sea level series. The British oceanographer Philip Woodworth (1990, 1999) has analysed the mean sea level records of Amsterdam (1700 – 1925) and Brest (1807 -) in addition to that of Stockholm, and also a high water record of Liverpool (1768 onwards, but with large gaps). Applying quadratic regression over their entire record lengths he found a significant quadratic term in all four of them. Furthermore, this term was found to be quite similar for the four sites, corresponding to an ”acceleration” of 0.9 mm/yr per century. This confirms that the Stockholm result is not dependent on any specific conditions in the Baltic Sea but reflects a general phenomenon. It should be noted that the quadratic regression here is a mathematically convenient way of handling the data, but that from a geophysical point of view two

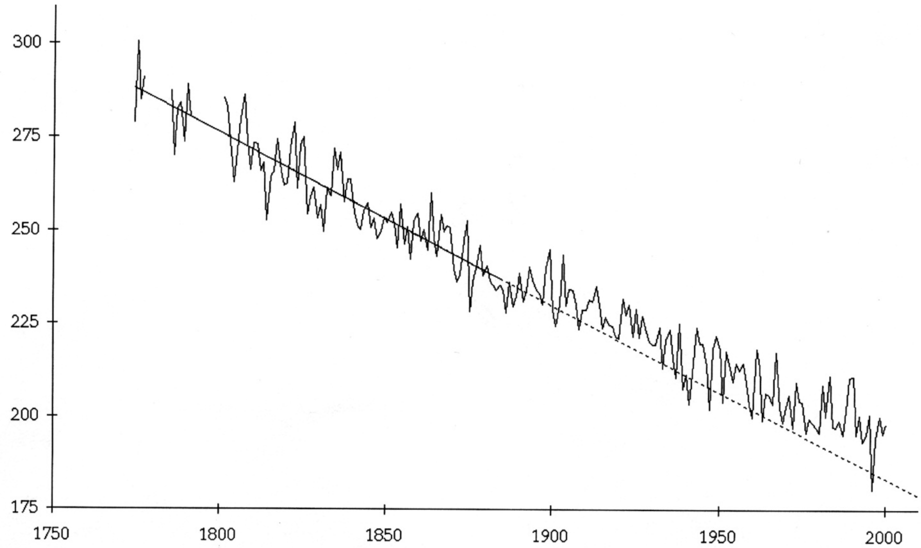


Figure 4-2. Annual mean sea levels (cm) at Stockholm 1774 – 2000, with the regression line for 1774 – 1884 and its extension into modern times. The climatic sea level rise is clearly perceptible. (Based on data in Appendix.)

different linear regressions better reflect the phenomenon, with a change in the sea level trend appearing in the second half of the 1800s.

Let us now return to the postglacial rebound model of Lambeck, Smither & Ekman (1998), treated in Section 3.6. As stated there the model also allows a determination of the climatic sea level rise. This is so because the rebound model in itself would predict present land uplift rates without any climatic effect, while the observed apparent land uplift rates include that effect. In principle, from formula (3-3),

$$\dot{z} = \dot{h} - \dot{N} - \dot{H}_a \tag{4-1}$$

Hence the rate of the climatic sea level rise can be included as an unknown in the modelling and, thereby, determined. The outcome of this operation was

$$\dot{z}\,(1892\text{-}1991) = 1.05 \pm 0.25 \text{ mm/yr}$$

The value represents the sea level rise during the 100-year-period 1892 – 1991, since that is the common time period for the calculation of the apparent land uplift rates of Ekman (1996) used in the above modelling. Recently, according to Lidberg et al (2007), mentioned in Section 3.6, continuous satellite positioning used instead of the rebound model has yielded a similar result, although somewhat more uncertain.

Now the possibility opens up to combine the obtained value of $\dot{z}$ with that of $\Delta\dot{z}$ above. The value of $\dot{z}$ agrees almost precisely with that of $\Delta\dot{z}$, showing that the climatic sea level rise during the end of the 1700s and most of the 1800s was close to zero,

$$\dot{z}\,(1774\text{-}1884) = 0.0 \pm 0.4 \text{ mm/yr}$$

as found by Ekman (1999).

The results above are in good accordance with the sparse knowledge from glaciers as compiled by the American-New Zealand climatologist Richard Warrick and the Dutch meteorologist and glaciologist Johannes Oerlemans (1990). The lengths of the glaciers have been more or less constant during the 1700s and most of the 1800s, followed by a quite abrupt change in the second half of the 1800s to decreasing lengths due to melting, a process still going on; see Figure 4-3.

How do the results above comply with the global averaging of sea level trends? Well, the global averaging is not so simple as it might seem. Already Gutenberg faced the problem of the irregular geographical distribution of the mareographs. He grouped the stations into a smaller number of more equally spaced regions and then took the average of all regional mean trends. Another problem to be faced is the elimination of other sea level changes than the global rise. The point here is to use only those sea level records that cover a sufficiently long time span. Trying to take both these things into account, the American oceanographer Tim Barnett (1983) arrived at an average sea level rise of 1.5 mm/yr for most of the past century. A long row of more or less similar attempts, compiled by the Intergovernmental Panel on Climate Change (IPCC) starting with Warrick & Oerlemans (1990), have yielded values between 1 and 2 mm/yr. Considering the set of results above, it would seem that a value nearer 1 than 2 mm/yr would be more plausible for the past century.

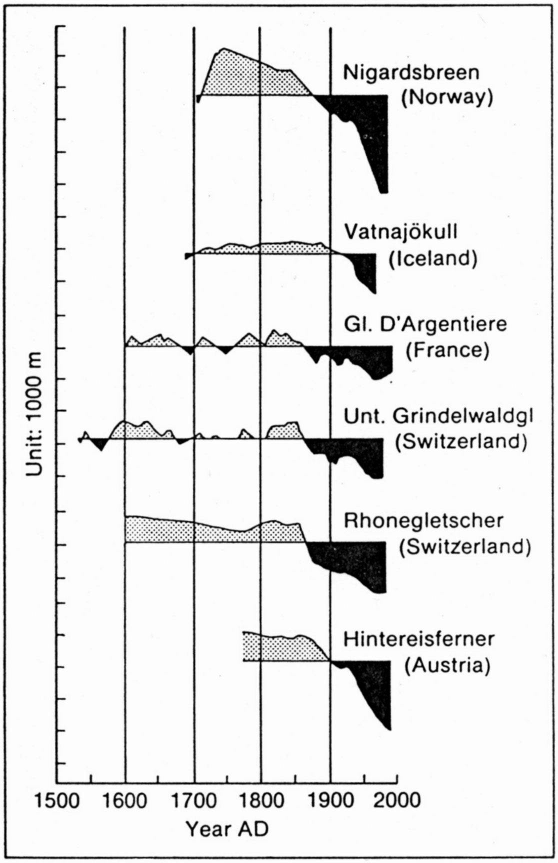


Figure 4-3. Length of glaciers during the last centuries, showing glacier melting since the end of the 1800s (Warrick & Oerlemans, 1990).

However, it should be noticed that the sea level rise may not be quite equal all over the globe. The sea level rise caused by *melting of glaciers* was determined through glaciological considerations by the American glaciologist Mark Meier (1984) to 0.5 mm/yr, with later estimates still keeping close to this value. This is not more than half of the observed sea level rise. An effect of the same order should be caused by *thermal expansion of the sea water*, at least its upper layers, as suggested by the American group of oceanographers and climatologists Vivien Gornitz, Sergej Lebedeff and James Hansen (1982), later confirmed through other theoretical estimates. This quantity may well be different in different regions. In case the large ice sheets over Greenland and Antarctica start melting also the gravity field will change and produce a geoid change, i.e. a gravitational change of the sea level. Also this quantity will be a function of location.

Recently, the fourth IPCC scientific assessment through Bindoff & Willebrand et al (2007) has arrived at an average global sea level rise of 1.7 ± 0.5 mm/yr for the past century. This is still compatible with the Stockholm and Baltic Sea results. An overview of the rates of the climatic sea level rise obtained through the different methods treated in this chapter is given in Table 4-1.

Table 4-1. Overview of rates of the climatic sea level rise determined by different methods (mm/yr). B indicates Baltic Sea.

Rates during the 1900s		
(1)	Geophysical rebound model & sea level (B)	1.05 ± 0.25
(1a)	Satellite positioning & sea level (B)	1.2 ?
(2)	Global average of sea level	1.7 ± 0.5
(3)	Glacier melting & sea water expansion	c. 1.0
Change in rate from the 1700s and 1800s to the 1900s		
(4)	Stockholm sea level series (B)	1.0 ± 0.3
Rates during the 1700s and 1800s		
(5)	Combination of (1) and (4) above (B)	0.0 ± 0.4
(6)	Glacier lengths	c. 0.0

5. Winter sea level changes and the atmosphere

5.1 Reversed currents and the water-works

In 1574 an Italian scientist, Appolonius Menabenus, went to Stockholm to become personal physician to the King of Sweden. He arrived by boat in spring when the ice still covered this part of the Baltic Sea. He therefore had to disembark the ship in the Stockholm archipelago and walk on the ice to reach Stockholm and the Royal Palace, an experience that he did not appreciate. He stayed at the Royal Palace for five years; then he left and returned to the south.

On returning, Menabenus (1581) wrote an essay about a remarkable phenomenon that he had witnessed several times during his stay in Stockholm. The Royal Palace there is situated on the shore of an island in the outlet of Lake Mälaren to the Baltic Sea; see Figure 5-1. From the palace you can easily study the water streaming through the outlet, from Lake Mälaren in the west to the Baltic Sea in the east. But now and then something strange occurs. Menabenus (1581) writes:

”The people in Stockholm observe, six or seven times per year at what appears to them to be irregular intervals, that the water is streaming in the reverse direction [from the sea to the lake], during five days or more each time. At these events people gather and stand for a long time looking at the reversed current, expressing their great wonder at the phenomenon and saying that they do not know the reason for it.”

Menabenus himself believed that this *reversed current* was a consequence of the tides, obviously not realizing that there were no tides in the Baltic. In any case, the duration of each event was far too long to be a tidal effect.

In reality, the cited text is the first written account of the peculiar *long-term sea level variations* of the Baltic Sea, driven by *winds* over northern Europe and the Baltic entrance. Such a long-term high water in the Baltic will make Baltic Sea water flow into Lake Mälaren, causing a reversed current in its outlet.

Figure 5-1. The outlet of Lake Mälaren (right) to the Baltic Sea (left) with the Royal Palace (about 1580). Here the water during certain conditions may flow in the reverse direction. (From Hogenberg's collection of engravings "Civitates orbis terrarum".)

The events of the reversed currents also had practical consequences. In the outlet, close to the Royal Palace, there was a water wheel driving some kind of pumps intended to supply the central parts of Stockholm with running water, mainly for washing purposes. This construction was based on the condition that the water in the outlet was running from the lake to the sea. When the water was running in the opposite direction, from the sea to the lake, the water-works could not be used! This problem made King Gustaf Adolf (1630), on his way to the war in Germany, order the governor of Stockholm to add a construction to it, namely "a horse mill under the bridge, by which the pumps can be driven when the water in the sea flows into the lake". These events were obviously common enough for the King to engage himself in them, which seems to confirm the observations of Menabenus.

It is interesting that Menabenus gives approximate mean values of both frequency and duration of the reversed currents. A frequency of six or seven times per year and a duration of five days or more imply that reversed currents occurred at least 30 days per year. This can be compared with the later water level observations at the Stockholm sluice, treated in Section 4.1. These observations were actually performed on both sides of the sluice, i.e. both in the lake and in the sea. Because of this the number of days with the sea higher than the lake, causing the reversed currents, can be accurately determined, at least after the mid 1800s (see Lilienberg, 1891). For the 40-year-period 1850 – 1889 we find an average number of days with reversed currents of 38 days per year. Thus Menabenus' estimate from 1581, as well as the King's order of 1630, is in good agreement with the water level data 300 years later. The phenomenon of reversed currents still occur, but only on rare occasions as the lake level has been artificially regulated since 1943.

5.2 Winds or air pressure?

On the opposite side of the Baltic, the Swedish fortifications engineer Erik Dahlbergh (1681) was mapping the innermost part of the Gulf of Finland and the river Neva discharging itself there. At this location there was at that time a town called Nyen with a fortress close to the water. On his map Dahlbergh made a note on the behaviour of the sea level there during storm of certain directions:

"When a westerly, south-westerly or north-westerly storm is blowing from the Baltic Sea, the water in the river Neva at Nyen [in the mouth of the river] rises more than 4 Swedish ells [8 feet] above its ordinary level. This causes great damage to the small fortress now situated there."

In modern units this means that Dahlbergh had found that storm winds could raise the sea level locally by more than 2.4 m. A few decades later the town was destroyed by Russian forces who instead started building a new city there, St. Petersburg. The Russians soon had to learn the same lesson as the Swedes had had to do.

The role of winds for the level of the Baltic Sea in a more general sense was first treated in a text on the Baltic by Petrus Lagerlöf (1698). Lagerlöf was a Swedish historian, but he was much interested also in geographical matters. Lagerlöf (1698) states:

"The Baltic Sea has no real tides that regularly make its water come and go. Instead, its natural flow seems to be towards the entrance [Öresund] only. However, a persistent north-westerly wind of long duration will not only prevent its natural outflow, but also push a lot of water from the

North Sea into the Baltic. This will cause a general rise of the level of the Baltic Sea.”

This is the first description and explanation of the special *long-term sea level variations* of the Baltic Sea. As can be seen, Lagerlöf claimed that a *steady wind field* over the Nordic area would change the distribution of water between the North Sea and the Baltic, changing the Baltic Sea level as a whole. It was to take two centuries before it could be shown that this was, indeed, correct.

Lagerlöf does not stop here but goes one step further. He could now give an explanation of the origin of the reversed currents discussed in the previous section:

”As a consequence also the salt [Baltic Sea] water at Stockholm becomes higher than Lake Mälaren, and thus causes a reversed current in the outlet there.”

Hence, long-term westerly winds would cause a current there from east to west, which is not only opposite to normal but also in the opposite direction to the wind. It is quite understandable that this caused wonder among the inhabitants.

In Chapter 2 we saw how Celsius was the first to determine a value of the rate of the water decrease, i.e. the postglacial land uplift. Moreover, since 1722 he had measured air pressure and temperature in Uppsala. Inspired by Celsius’ investigations the Swedish physicist and medical officer Nils Gissler (1747) investigated the effect of air pressure on the sea level. Gissler set up a sea level scale, one of the first in the Baltic Sea, at Härnösand on the west coast of the Gulf of Bothnia. There he observed the sea level throughout the year 1746, at the same time as he measured the air pressure with a barometer. Gissler found a close relationship between sea level and air pressure:

”From the above observations I have found that, for the most part, whenever the barometer rises the sea level falls, and whenever it falls the sea level rises.”

Gissler thus had discovered an *inverted barometer effect* in the sea level. However, on some occasions the inverted barometer effect seemed to fail because of strong temporary winds.

Gissler also notes that the lowest sea level was observed in April, while the highest sea level was observed in December. This is in agreement with modern knowledge of the seasonal variations in the Baltic Sea level. The difference between the highest and the lowest sea level readings was 33 (Swedish) decimal inches, which equals 1.0 m, only slightly smaller than normal according to modern data. In this connection an interesting remark is made by Gissler: ”Last autumn and before Christmas a persistent and serious winter was awaited in vain as long as the water always stood at the same height and near its highest level.” Without Gissler knowing it this is related to the wind assumption of Lagerlöf; persistent westerly winds will cause both a high winter sea level and a high winter temperature, as will be discussed in Section 5.6.

During the second half of the 1700s a scientific mapping of nearly all coasts and archipelagos of the Baltic Sea was performed, resulting in accurate sea charts. Since at that time Finland as well as parts of northern Germany belonged to Sweden, this was mainly a Swedish affair. The leader of the work for a long time was the naval officer and hydrographer Johan Nordenankar. Based on his wide experiences, Nordenankar (1792) presented a study of the effects of winds on the currents and the level of the Baltic Sea. As Lagerlöf a century earlier, he advocated a long-term effect on the Baltic as a whole caused by steady winds transporting water from the North Sea into the Baltic. In the Baltic entrance the German-Swedish physicist Johan Carl Wilcke (1771) had found that salinity increased during westerly winds, vaguely supporting the existence of a water transport through the entrance. But Nordenankar added another phenomenon, a *short-term sea level variation* caused by *storms* redistributing water within the Baltic. He claimed that a south-westerly storm caused a lot of water to flow into the Gulf of Finland, and that a south-easterly storm in the same manner caused a lot of water to flow into the Gulf of Bothnia. For the innermost part of the Gulf of Finland the German-Russian physicist Wolfgang Ludwig Krafft (1777) had presented data from Kronstadt at St. Petersburg showing that floods there were connected to south-westerly storms, but it was not known to what extent this was a local effect.

So, there were now three possible explanations of the variations of the sea level in the Baltic Sea:

1. Air pressure variations causing an inverted barometer effect, as proposed and already confirmed by Gissler. This could be investigated closer by further combining sea level and air pressure observations.

2. Short-term winds redistributing water within the Baltic Sea, as proposed by Nordenankar. This could be investigated by combining sea level and wind observations, preferably at several places in different parts of the Baltic.

3. Long-term winds transporting water between the Atlantic Ocean (the North Sea) and the Baltic Sea, as proposed originally by Lagerlöf. To be investigated this would require combining sea level observations in the Baltic with wind observations outside the Baltic, both made over a long period.

5.3 Storms and short-term sea level variations

It was not long before one thought that one had solved the problem. The Finnish-Swedish geodesist and hydrographer Nathanael Gerhard Schultén (1806) argued for the applicability of a theoretical relation between sea level change and air pressure change, 1 cm/hPa in modern units. On the basis of this he arrived at the conclusion that the air pressure was the main cause of the Baltic Sea level variations. Winds were, according to him, unable to transport sufficient amounts of water within a reasonable time in order to produce any significant sea level variations (other than waves).

However, about 1810 a number of sea level stations with systematic sea level observations were established in harbours along the German Baltic coast. A generation later, 20 years of sea level data combined with wind direction data had been collected at one of the stations, Pillau in the south-eastern corner of the Baltic Sea. These two data sets were compared by G W Bannasch (1835), a German lecturer in navigation. His comparison showed that sea level there, as a rule, was highest during north-westerly winds, blowing towards the coast. Correspondingly, sea level was lowest during south-easterly winds, blowing outwards from the coast. Still, it was not known to what extent this was just a coastal effect.

About 1850 such sea level stations were established also along the other Baltic coasts, often at light-houses and pilot stations. In addition, sea level scales for practical use were set up in harbours. This proved valuable when an extra-ordinary event occurred: the great storm of 1872.

Storms of course had occurred before. A south-westerly storm in 1824 had caused the highest sea level ever observed in the Baltic Sea, 4.2 m above normal, in St. Petersburg in the innermost part of the Gulf of Finland. But the storm of 1872 was the first one allowing a scientific study of its effect on the level of the Baltic Sea. This was a north-easterly storm causing the sea level to reach a height of 3.4 m above normal at Travemünde and its surroundings in the south-western corner of the Baltic Sea. Because extensive coastal areas in both Germany and Denmark were flooded there was a great interest in having this event scientifically examined.

In Germany the harbour and canal engineer Otto Baensch (1875) collected sea level data from more than 20 stations along the German coast, which at that time covered the whole southern coast of the Baltic Sea. These data were compared with data on wind direction and wind force. It turned out that the sea level reacted almost instantaneously to the storm winds. It reacted strongly in the south-western Baltic but weakly in the south-eastern, partly reflecting the angle between the wind and the general coast-line.

In Denmark the physicist and water engineer August Colding (1876, 1881) carried out a most comprehensive investigation of the whole phenomenon. Just one week after the storm he had a request published in the leading Danish newspaper for sea level observations performed in Denmark during the storm. At the same time he arranged with the Danish foreign ministry to ask for access to similar observations performed in the other countries around the Baltic Sea. In this way he succeeded in obtaining sea level observations from no less than 135 stations in Denmark, 30 stations in Germany (including today's Poland), 5 stations in Russia (including today's Lithuania, Latvia and Estonia), 20 stations in Sweden and 3 stations in southern Norway. In addition he collected data on air pressure, wind direction and wind force. Fortunately, he was able to obtain wind velocities as well from some stations along the Swedish coast, which enabled him to convert all estimates of wind force to approximate wind velocities.

After analysing this large amount of material Colding arrived at two important conclusions. The first one was that the height above normal to which a storm raises the sea level at a coast, ΔH, is proportional to the square of the wind velocity, w. Moreover, it is proportional to the length of the open sea over which the wind is blowing, s, and inversely proportional to the depth of the sea, D. In summary,

$$\Delta H = \alpha \frac{w^2 s}{D} \qquad (5\text{-}1)$$

α being a numerical constant. Thus the sea level becomes especially high for very high wind velocities in combination with a large and shallow sea.

Colding's second conclusion was that the water over the entire Baltic Sea was involved. While sea level was raised in the south-west by 3 m it was lowered in the north-east by 1 m; see Figure 5-2. The sea level changed in a systematic manner all over the Baltic. Colding (1881) writes:

"The entire sea surface of the Baltic Sea was by the power of the storm brought considerably out of its general equilibrium, or normal state. That part of the Baltic Sea which had its normal level and which, remarkably enough, during the whole storm kept the normal level almost unchanged, was limited to a line from Stockholm down to Pillau. From this line of normal sea level, approximately perpendicular to the wind direction, the sea level lowers towards north-east, while the sea level from this line rises towards south-west."

Colding thus had discovered the existence of a *nodal line* during the storm, located somewhere in the middle of the Baltic Sea, going from Stockholm towards the south-eastern Baltic; see Figure 5-2. Later it was also found that resonance might occur with this as a nodal line.

Finally Colding found that the storm caused a sea level difference of 3 m across the Baltic entrance, the sea level being nearly 3 m above normal in the Baltic just to the south of the Öresund and close to normal in

Figure 5-2. Sea level change (m) due to the north-easterly storm of 1872. (Redrawn from Colding, 1881.)

the Kattegat just to the north of it. This caused a strong northgoing current in the Öresund attaining a speed of 1 ½ m/s (3 knots), directed more or less contrary to the wind.

Because of Colding's results the understanding of the behaviour of the Baltic Sea level had improved considerably. The solution concerning the three possible explanations of the variations of the sea level in the Baltic, given at the end of the previous section, now was the following:

1. *Short-term sea level variations* are to a limited extent caused by *air pressure variations* producing an inverted barometer effect.

2. *Short-term sea level variations* are to a larger extent caused by *winds redistributing water within the Baltic Sea.*

3. Long-term sea level variations form an unsolved and almost forgotten problem.

Items 1 and 2 had not only been solved but could also explain non-tidal sea level variations along the coasts of the oceans. Thus the air pressure effect also was found, one century after its discovery in the Baltic, in the Mediterranean Sea as well as in the Arctic Sea, and the wind effect (storm effect) was recognized also in the North Sea. Item 3, however, remained hidden in the dark, and there was no such phenomenon known anywhere else in the world.

5.4 Persistent winds and long-term sea level variations

At the end of the 1820s there were enough sea level data to allow a comparison of long-term sea level variations in different parts of the Baltic Sea. Such a comparison was never made at that time, but it is instructive to do it now. We therefore put together annual means of the sea level for the first common years of the three earliest sea level stations: Stockholm in the northern part of the Baltic proper, Swinemünde in the south-western part, and Pillau in the south-eastern part. The common time period of these stations begins in 1825 (ignoring some earlier years for which the Stockholm data are not original but have been transformed from København). Let us study the annual means for the first five years, 1825 – 1829. For each year we calculate the deviation of the annual mean sea level from the mean sea level of the whole period. In the case of Stockholm we also make a reduction for the land uplift of 5 mm/yr.

The result is shown in Table 5-1. It clearly reveals that interannual variations in different parts of the Baltic Sea are almost identical. This demonstrates the existence of a common sea level variation, a slow rise and fall of the Baltic Sea level as a whole. The figures in Table 5-1 are in good accordance with modern results discussed in Section 5.6 (Table 5-2). However, the pattern of Table 5-1 remained hidden for a generation; no one at that time combined such data from widely separated stations.

In reality, the long-term sea level variations began to reveal themselves when the first systematic sea level observations performed both inside and outside the Baltic Sea were collected. These observations were the ones made at light-houses along the Swedish coasts, together with

Table 5-1. Interannual sea level variation at the earliest sea level stations, in different parts of the Baltic, for the years 1825 – 1829 (cm).

Station	1825	1826	1827	1828	1829
Stockholm	13.4	- 6.9	- 1.5	1.5	- 6.3
Pillau	9.3	- 6.2	- 1.0	2.2	- 4.5
Swinemünde	7.0	- 6.9	- 0.9	1.8	- 1.0

meteorological observations. Monthly and annual means of the sea level for four common years were published by Axel Erdmann (1856), a Swedish geologist. He refrained from drawing conclusions, but the numerical results contain interesting information. Excluding uncertain sea level stations we are left with a couple of stations inside the Baltic, in the Baltic proper, and a couple of stations outside the Baltic, in the Kattegat and Skagerrak. The annual means of the sea level inside the Baltic turn out to be comparatively high for two of the four years, and comparatively low for the two other years. The annual means outside the Baltic show the same pattern. This is an indication of the long-term sea level inside the Baltic being correlated with the sea level outside it. It should also be mentioned that Erdmann notes a common seasonal variation, with a minimum normally in spring and a maximum normally in autumn.

The seasonal variation had been observed already by the Danish naval officer Peder Mandrup Tuxen (1833) in the data from København. It had also been observed in the data from Swinemünde by the German military geodesist Johann Jacob Baeyer (1840), and then at all stations along the Baltic south coast by the German physicist and harbour engineer Gotthilf Hagen (1844). Baeyer suspected that it was due to thermal expansion and contraction of the sea water, but found that that effect would be too small.

A few decades later, extended records of data from the earlier mentioned stations inside and outside the Baltic were collected and analysed by the Swedish hydrographer Lars Arvid Forssman (1876). He produced

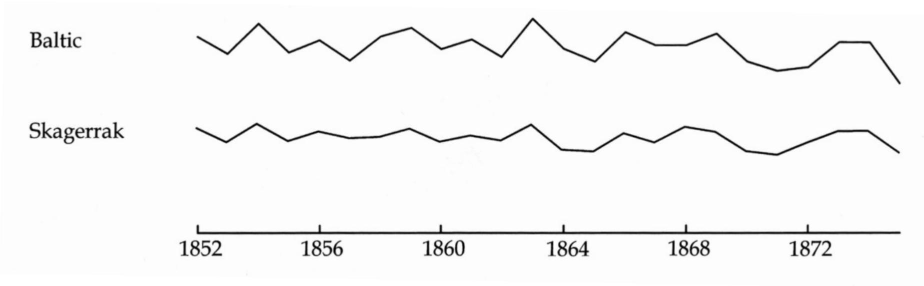


Figure 5-3. Interannual sea level variation 1852 – 1875 (of the order of 10 cm) inside the Baltic (Stockholm) and outside the Baltic (Nordkoster in the Skagerrak). (Redrawn from Forssman, 1876.)

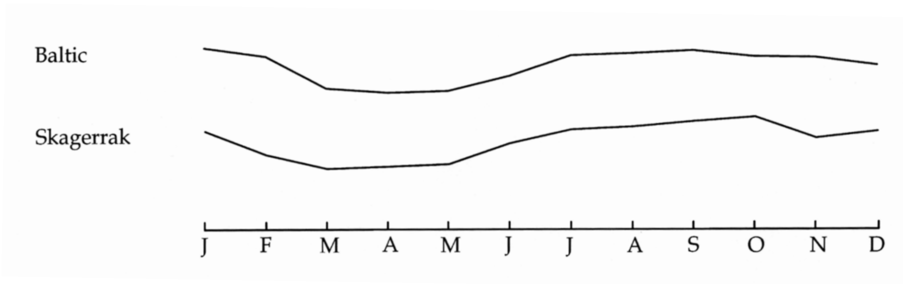


Figure 5-4. Average seasonal variation for the same stations and the same time period as in Figure 5-3 (on the same scale).

a set of curves showing the *interannual variation*, obtained from the annual means, of all the stations. The interannual variation, of the order of 10 cm, turned out to be almost equal for all stations, inside as well as outside the Baltic; see Figure 5-3 showing the two most reliable ones. From this Forssman concludes that the long-term sea levels inside and outside the Baltic are in some way connected with each other. Forssman also produced a set of curves showing the *seasonal variation*, based on the monthly means, of all the stations. This was an average seasonal variation over the available years. Also this variation, of the order of 10 cm too, turned out to be almost equal for all stations, inside as well as outside the Baltic; see Figure 5-4 showing the same two stations as above. From Figures 5-3 and 5-4 we may also note that the long-term variations have somewhat larger amplitudes inside the Baltic than outside. Later it was found by Blomqvist & Renqvist (1914), in their paper treated in

Chapter 3, that inside the Baltic the amplitudes tend to increase from south-west to north-east.

Altogether it appears that sea levels inside and outside the Baltic are in some way connected, provided the time scale exceeds one month or so. Forssman was inclined to believe that varying precipitation, including water contribution from rivers, was the main cause of this effect. However, with some hesitance he also kept the door open for varying wind conditions, an old and almost forgotten idea taken up again by Hagen (1865) and, in more detail, by the German oceanographer Heinrich Adolf Meyer (1871).

On the German coast the sea level station at Swinemünde offered a very long and reliable sea level series, analysed by the German geodesist and hydrographer Wilhelm Seibt (1881 & 1890). Seibt studied the seasonal variation in the data. He realized that precipitation and water contribution from rivers could not be the cause, since the additional water would be able to leave through the Baltic entrance during the time allowed. A test showed that neither could air pressure be the cause, their long-term variations being too small.

Now, while Forssman compared the seasonal variation between different stations, Seibt compared the seasonal variation between different decades. There was some similarity between the decades which allowed him to calculate an average seasonal variation for the whole time period. But the interesting thing here is something that Seibt did not comment upon. Studying his seasonal variation for different decades it appears that in one of the seasons there are notable differences between the decades. That season is winter. We will deal with the role of winters later on.

By now there had been proposed four different explanations of the long-term sea level variations in the Baltic Sea, three of which had soon been more or less rejected:

A. Temperature variations. Rejected as having a too small effect on the sea level.

B. Precipitation variations (including variations in river discharge). Rejected as having a too short-lived effect on the sea level.

C. Air pressure variations. Rejected as being too small on this time scale.

D. Varying wind conditions. The only remaining explanation, but does it hold?

In the 1870s oceanographic expeditions using research vessels started. The first oceanographic expedition covering the Baltic Sea, carried out in 1877, was initiated and headed by the Swedish oceanographer Fredrik Laurentz Ekman. Through this expedition layers of different salinity and temperature were identified in the Baltic Sea as well as in the Kattegat and the Skagerrak. Ekman introduced the concept of reaction currents explaining the exchange of water and salt between the ocean and the Baltic Sea. In this connection Ekman (1893) also was able to give a realistic explanation of the long-term sea level variations of the Baltic:

”In the Skagerrak and the Kattegat the surface water can, by strong and persistent winds from the North Sea, be driven back and be replaced by North Sea water, causing the salinity in the Skagerrak surface water even along the Swedish Skagerrak coast to increase to 3.5 %. Although W and SW winds are not really favourable for transporting the surface water of the Kattegat into the Baltic Sea, this can nevertheless occur as a consequence of the rise of the sea level in the Skagerrak and the Kattegat, and the fall of the sea level in the south-western Baltic, caused by such winds. Thereby the surface current in the Öresund can be reversed. … Hence, for every period of stronger winds from the North Sea the total amount of water in the Baltic Sea is increased.”

A partial confirmation of this through the study of sea level and air pressure gradients was obtained by the German geophysicist Friedrich Kühnen (1916). He found that the monthly mean sea levels at the German Baltic Sea coast as well as at the German North Sea coast were quite dependent on the air pressure at the Åland Islands far to the north, in the middle of the Baltic Sea. His explanation of this was that a low air pressure at the Åland Islands implies a north-south air pressure gradient, which in its turn also causes a westerly wind.

Further confirmation was provided by the Swedish hydrographer Folke Bergsten (1931). He widened the meteorological perspective, explaining the long-term sea level variations at the Scandinavian North Sea coasts by varying wind conditions due to changing relations between the Icelandic low pressure area and the Azores high pressure area (today's North Atlantic Oscillation, NAO). These sea level variations were then transmitted into the Baltic Sea as a whole; the correlation between the Baltic and the Kattegat long-term sea levels was found to be as high as 0.95.

Moreover, the Finnish oceanographer Ilmo Hela (1944) found a strong correlation between a high long-term sea level in the Baltic and a south-westerly or westerly mean wind direction at the Baltic entrance, and a corresponding correlation between a low long-term sea level and a north-easterly or easterly mean wind direction. From this he concluded that a high annual mean sea level should correspond to a mild winter and a rainy summer, a low annual mean sea level to a severe winter and a dry summer.

The general picture of the sea level variations in the Baltic Sea can now be completed and summarized in the three following items:

1. Short-term sea level variations – on the time scale of days – are to a limited extent caused by air pressure variations producing an inverted barometer effect.

2. Short-term sea level variations – on the time scale of days – are to a larger extent caused by winds redistributing water within the Baltic Sea. This mainly affects the northern, eastern and south-western ”ends” of the Baltic.

3. *Long-term sea level variations* – on the time scale of months and years – are caused by *persistent winds redistributing water between the Atlantic Ocean (the North Sea) and the Baltic Sea*. This affects the Baltic as a whole.

Item 3 shows that the early hypothesis of Lagerlöf (1698) was, in fact, correct. Why, then, did it take such an extremely long time to prove it? The main problem seems to have been the difficulty in realizing that the winds affect the Baltic Sea through two different mechanisms, items 2 and 3. This difficulty is most evident in the southern part of the Baltic, where much of the older sea level data were collected. For example, a south-westerly wind there will start by causing a low sea level. In the long run, however, the scene will change and finally end up with the same wind causing a high sea level! When these different time perspectives are mixed up, the interpretation of the sea level data becomes confused.

5.5 Winters and the varying seasonal sea level variation

We noted earlier that the average seasonal variation in the sea level is characterized by a low in spring and a high in autumn, the amplitude being of the order of 10 cm. The variation is, in fact, somewhat asymmetric so that it can be described by the sum of two harmonic (sine) variations, a major one of period one year and a minor one of period half a year, as found already by Blomqvist & Renqvist (1914) and Kühnen (1916).

Studying the sea level data of Swinemünde and a few other long-lived sea level stations, the German hydrologists Arthur Hahn and Ernst Rietschel (1938) found something unexpected. The difference between autumn and spring sea level tended to increase over the century of data available. Following Bergsten (1931), they attributed this to meteorological and oceanographic changes in the North Atlantic Ocean.

Half a century later the long Stockholm series was investigated by the author and his oceanographic colleague Anders Stigebrandt (Ekman & Stigebrandt, 1990) with respect to the seasonal sea level variation. They applied Fourier analysis to the monthly mean sea levels for the years 1825 – 1984. The result of the analysis was an *increase in the amplitude of the seasonal sea level variation* (with the annual period) from 8 to 11 cm. This increase could be shown to be statistically significant at the 99 % level. (For the variation with the semi-annual period there was no significant change.) As to the origin of the increase in amplitude they suggested a changed seasonal density effect due to a movement of the oceanic polar front, or a changed seasonal wind stress over the north-eastern Atlantic Ocean and the North Sea.

Later Ekman (1998) showed that the increase in the amplitude of the seasonal variation is mainly due to *changes during the winter season*, with increasing sea levels in early winter and decreasing sea levels in late winter. This has led to a shift in the (rather flat) maximum towards the end of the year. Comparing the sea level data with wind data from the Baltic entrance for the whole period 1825 – 1984 he found that the main origin of the amplitude increase is a secular change in the winter wind conditions, with increasing south-westerly winds in early winter and decreasing south-westerlies in late winter.

Concentrating on the 1900s only but including not only Baltic but also North Sea stations, the amplitude increase was confirmed by the German geophysicist Hans-Peter Plag and the Greek-British oceanographer Mikis Tsimplis (1999). Analysing also meteorological data from the same area they concluded that the change in the seasonal sea level variation, especially for the last two decades, was forced by a change in the atmospheric circulation, i.e. in the wind stress over the sea surface.

Now, as mentioned the seasonal variation has a low in spring and a high in autumn, implying that sea level would be close to normal in summer and winter. However, this is a purely statistical way of looking at the whole thing, averaging all years. In reality, winter sea level shows considerable, sometimes dramatic, differences between individual years, several times larger than the average seasonal variation itself. Hence, what is really interesting from a geophysical point of view is not the seasonal variation but rather the behaviour of the sea level in winters. This is what we will turn to now.

5.6 Long-term sea level and changes of winter climate

In order to study the long-term sea level variations of the Baltic Sea there is one station that should be especially worth-while to use. That one is Stockholm. Why is Stockholm so special in this respect? The background to this is the following.

As we have seen, short-term and long-term sea level variations of the Baltic Sea behave in completely different ways. The reason for this is the fact that the Baltic Sea is a semi-enclosed basin, reacting like a fiord, as explained by Stigebrandt (1980) and Samuelsson & Stigebrandt (1996). The long-term variations (one month or more) are mainly externally driven variations, affecting the whole Baltic Sea, but with maximum amplitudes in the north and minimum amplitudes at the Baltic entrance in the south. More rapid external variations are filtered out due to the choking effect of the narrow and shallow Baltic entrance. The short-term vari-

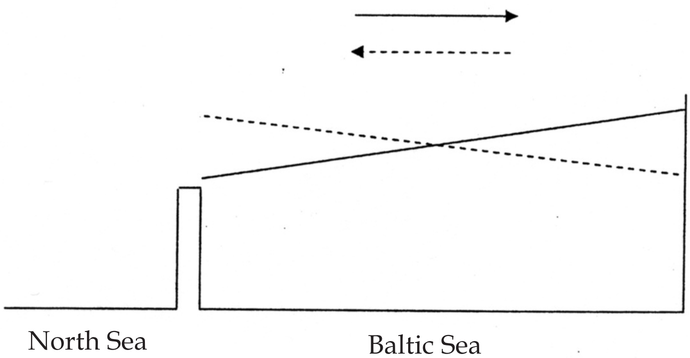


Figure 5-5. The short-term effect on the Baltic Sea level caused by a temporary wind from south-west (continuous line) or north-east (dashed line). Stockholm is close to the node in the middle.

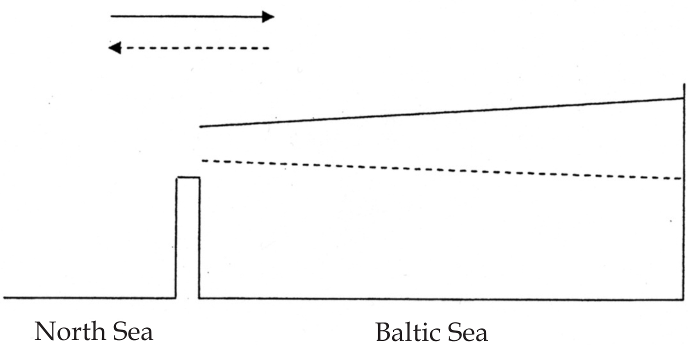


Figure 5-6. The long-term effect on the Baltic Sea level caused by a persistent wind from south-west (continuous line) or north-east (dashed line).

ations (less than one month) are mainly internally driven variations, with maximum amplitudes in the far north and the far south, and a nodal line close to Stockholm in the middle. Thus nature has given the Stockholm sea level remarkable properties: Short-term sea level variations are nearly eliminated, while the long-term sea level variations are those of the North Sea in magnified form; see Figures 5-5 and 5-6. This makes *Stockholm an ideally situated station for studying long-term sea level changes*. Moreover, as we know, Stockholm has the longest sea level record in the world, commencing in 1774.

The geographical pattern of the wind-induced long-term sea level variation in the Baltic Sea and the adjacent parts of the North Sea has been determined through computations of the interannual variation by Ekman (1996a); see Table 5-2 and Figure 5-7. Here all values have been reduced to a common time period, the 100-year-period 1892 – 1991, through comparisons with Stockholm in a manner similar to that for the land uplift rates in Chapter 3. Thus the values in Table 5-2 (and Figure 5-7) are given in a consistent system. Almost exactly the same pattern as for the interannual variation was found for the seasonal (both annual and semi-annual) variation, confirming their common origin.

Now, in a series of papers the author has analyzed the Stockholm sea level record with respect to the long-term changes, some of the results being collected in Ekman (1999). To start with it was found that extreme annual means in the level of the Baltic Sea are almost exclusively created by extreme monthly means during *winter* and, thereby, by anomalous wind conditions during winter. The role of winters here is mainly due to the fact that winds tend to be stronger and more persistent during late autumn and winter, and wind stress over the sea surface is proportional to the square of the wind velocity. Next it was revealed that the interannual sea level variability of the Baltic Sea has decreased significantly from the end of the 1700s to the beginning of the 1900s, and that after that it has increased again. Precisely the same changes were found to apply to the interannual winter wind variability as deduced from a long series of wind direction observations close to the Baltic entrance. Thus there should also be corresponding changes in the winter air pressure distribution.

The Swedish oceanographer Helén Andersson (2002) confirmed a strong correlation between the Stockholm sea level in winter and the air pressure distribution in winter. The optimal correlation with the Stockholm sea level, based on data from the 1900s, was found by her for the south-north air pressure difference across the North Sea, between the Netherlands (De Bilt) and southern Norway (Oksøy). The correlation obtained was as high as 0.89. A high correlation was found by her also across the whole of Europe, and a somewhat lower correlation for the North Atlantic Oscillation; compare also the air pressure studies by the German oceanographers and meteorologists Wolfgang Matthäus and Holger Schinke (1994).

Table 5-2. Long-term (interannual) sea level variations at sea level stations reduced to the 100-year-period 1892 – 1991, expressed as standard deviations of the apparent land uplift rate (mm/yr). (May be converted to standard deviations of an annual mean (cm) by multiplying by 28.8.) Stations are in anti-clockwise order around the Baltic (grouped by countries).

Station	Lat.	Long.	Years	St. dev.
Kronstadt	59 59	29 47	1841 – 1916	0.24
Hamina	60 34	27 11	1929 –	0.24
Helsinki	60 09	24 58	1904 –	0.23
Hanko	59 49	22 58	1888 –	0.21
Turku	60 25	22 06	1922 –	0.22
Degerby (Åland)	60 02	20 23	1924 –	0.20
Lemström (Åland)	60 06	20 01	1889 –	0.20
Lypyrtti	60 36	21 14	1858 – 1922	0.19
Rauma	61 08	21 29	1933 –	0.21
Mäntyluoto	61 36	21 29	1913 –	0.22
Kaskinen	62 23	21 13	1927 –	0.22
Vaasa	63 06	21 34	1913 –	0.22
Pietarsaari	63 42	22 42	1915 –	0.23
Raahe	64 42	24 30	1923 – 1975	0.23
Oulu	65 02	25 26	1913 –	0.24
Kemi	65 44	24 33	1920 – 1976	0.24
Furuögrund	64 55	21 14	1916 –	0.23
Ratan	64 00	20 55	1892 –	0.22
Draghällan	62 20	17 28	1898 –	0.21
Gävle	60 41	17 10	1896 –	0.20
Björn	60 38	17 58	1892 – 1976	0.20
Stockholm	59 19	18 05	1774 –	0.20
Grönskär	59 16	19 02	1849 – 1930	0.20
Södertälje	59 12	17 38	1869 – 1969	0.19
Landsort	58 45	17 52	1887 –	0.19
Visby (Gotland)	57 39	18 18	1916 –	0.17
Ölands norra udde	57 22	17 06	1887 –	0.18
Kungsholmsfort	56 06	15 35	1887 –	0.17

Ystad	55 25	13 49	1887 – 1986	0.15
Klagshamn	55 31	12 55	1930 –	0.13
Varberg	57 06	12 13	1887 – 1981	0.14
Smögen	58 22	11 13	1895 –	0.13
Oslo	59 54	10 45	1914 –	0.16
(Nevlunghavn	58 58	9 53	1927 – 1965	0.12)
Tregde	58 00	7 34	1928 –	0.08
Stavanger	58 58	5 44	1914 –	0.10
Bergen	60 24	5 18	1883 –	0.12
Heimsjø	63 26	9 04	1928 –	0.16
Narvik	68 26	17 25	1906 –	0.20
Esbjerg	55 28	8 27	1889 –	0.16
Hirtshals	57 36	9 57	1891 –	0.13
Frederikshavn	57 26	10 34	1893 –	0.11
Århus	56 09	10 13	1889 –	0.09
Fredericia	55 34	9 46	1890 –	0.08
Slipshavn	55 17	10 50	1890 –	0.09
Korsør	55 20	11 08	1890 –	0.10
Hornbæk	56 06	12 28	1891 –	0.14
København	55 41	12 36	1889 –	0.12
Gedser	54 34	11 58	1892 –	0.12
Marienleuchte	54 30	11 15	1882 – 1944	0.12
Travemünde	53 58	10 52	1855 –	0.12
Wismar	53 54	11 28	1849 –	0.13
Warnemünde	54 11	12 05	1856 –	0.13
Swinemünde	53 55	14 16	1811 –	0.14
Kolberg	54 11	15 34	1825 – 1935	0.15
Pillau	54 39	19 54	1816 – 1944	0.19
Liepaja	56 32	20 59	1865 – 1936	0.21

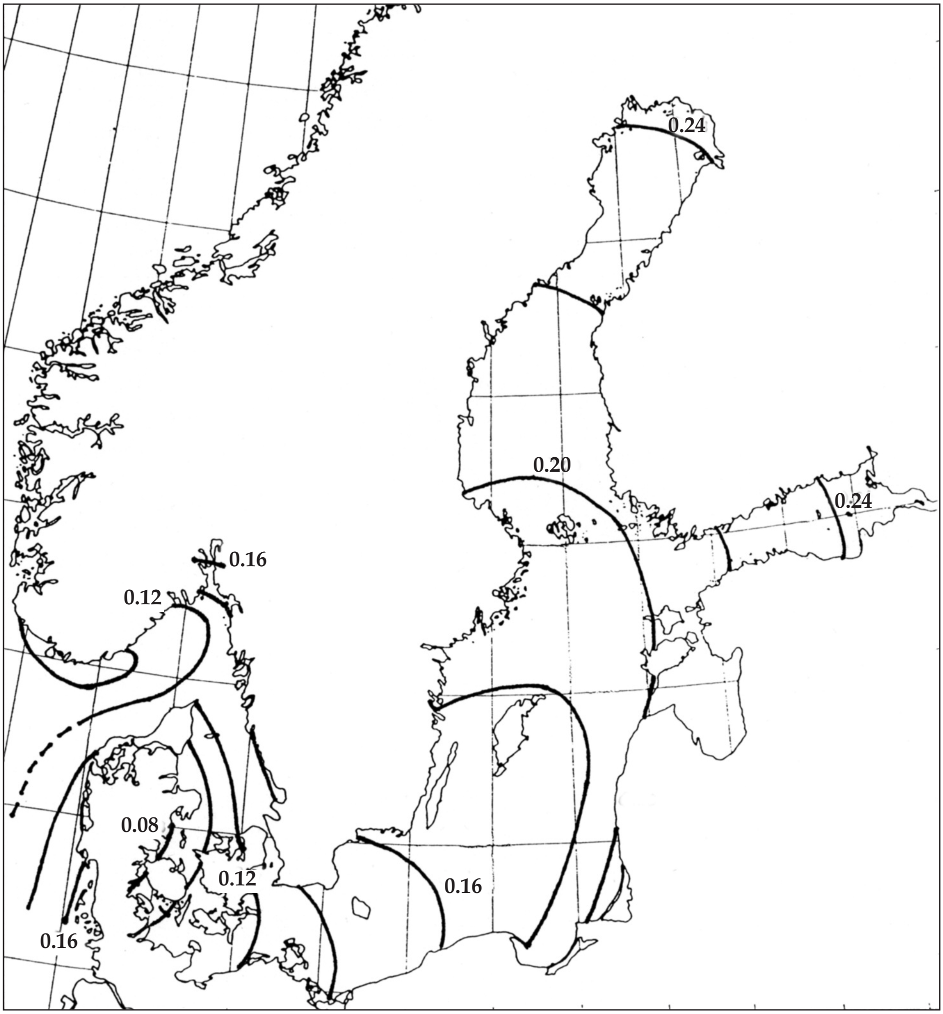


Figure 5-7. Geographical pattern of the long-term sea level variation in the Baltic Sea and adjacent waters, based on Table 5-2 (Ekman, 1996a).

In order to fully utilize the important Stockholm sea level data the author now recomputed the whole series of monthly (and annual) means from original documents; see Chapter 1 (Section 1.3) and Appendix. Using this recalculated and complete set of monthly mean sea levels, Ekman (2003) has constructed a series of winter sea level deviations for the years 1774 onwards, a quantity that may serve as a winter climate index for northern Europe since 1774.

This winter sea level deviation is the difference between winter mean sea level and normal sea level at Stockholm. Winter mean sea level is here defined as the average of the monthly means for January, February and March. Normal sea level is defined by two linear trends: one before 1865 representing the postglacial land uplift and one after 1865 representing the land uplift together with the global sea level rise occurring since the late 1800s. The numerical values of the winter sea level deviation for the years 1774 – 2000 are given in Table 5-3; they are also graphically illustrated in Figure 5-8. Large positive values – high sea levels – mean large south-north air pressure differences and dominating westerly winds over northern Europe. Large negative values – low sea levels – mean large north-south air pressure differences and dominating easterly winds over the same area. The whole phenomenon may be called the *inter-winter sea level oscillation*. A visible effect of these persistent wind fields is shown in Figure 5-9.

As can be seen from Table 5-3, the inter-winter sea level oscillation spans between the extreme values + 40 cm and - 37 cm, which thus are the extreme deviations of winter mean sea level from normal sea level. To give a quick impression of the climatic character of the winter sea level deviation, Ekman (2003) has shown two things, see Table 5-4 (page 96): First, winter sea levels above 30 cm coincide with winter winds around WSW, winter temperatures about 5°C above normal, and about 15 % ice cover in the Baltic Sea. Second, winter sea levels below - 30 cm coincide with winter winds around ENE, winter temperatures from normal to 4°C below, and 40 – 100 % ice cover in the Baltic Sea. (The lower correlation with low temperature and large ice extent should be due to these quantities being sensitive not only to the wind direction but also to the degree of cloudiness.)

The winter sea level deviation basically measures the integrated effect of wind direction, wind speed and wind persistence over the North Sea and the Baltic entrance. Thus the primary relation should be between the sea level deviation and the air pressure difference causing the geostrophic wind field there. Using air pressure data from the 1900s from the optimal stations above, Ekman (2003) has determined, through linear regression, relationships between the *winter sea level deviation*, ΔH, and the *winter south-north air pressure difference across the North Sea*, Δp_N :

Table 5-3. Inter-winter sea level oscillation (deviations of winter mean sea level from normal sea level) at Stockholm 1774 – 2000 (cm). Also available as a computer file from the Permanent Service for Mean Sea Level (PSMSL).

Year	Level	Year	Level	Year	Level
1774	-1.4	1820	-18.0	1852	10.2
1775	4.7	1821	-4.1	1853	-7.6
1776	-14.0	1822	38.2	1854	1.7
1777	-9.4	1823	-33.1	1855	-6.4
		1824	6.9	1856	-2.0
1785	-19.9	1825	19.0	1857	-5.6
1786	-29.8	1826	-16.3	1858	7.3
1787	-7.1	1827	0.7	1859	19.2
1788	-6.7	1828	-5.7	1860	-2.4
1789	-0.3	1829	-16.8	1861	-3.1
1790	36.3	1830	-16.3	1862	-12.3
1791	10.6	1831	-23.6	1863	19.4
		1832	-8.6	1864	4.1
1801	(24.1)	1833	-14.7	1865	-8.1
1802	3.2	1834	20.2	1866	21.4
1803	-25.2	1835	26.1	1867	-0.3
1804	-16.5	1836	23.7	1868	18.4
1805	-10.5	1837	-1.6	1869	1.9
1806	8.3	1838	-13.8	1870	-14.2
1807	22.0	1839	21.7	1871	-18.4
1808	14.0	1840	-5.1	1872	-16.9
1809	-15.3	1841	-20.8	1873	-2.8
1810	8.9	1842	-14.8	1874	22.5
1811	-3.6	1843	6.0	1875	-24.6
1812	-12.2	1844	3.0	1876	-8.2
1813	0.8	1845	-15.6	1877	-8.1
1814	-27.9	1846	13.1	1878	11.1
1815	-15.3	1847	-11.7	1879	-9.9
1816	3.3	1848	-27.2	1880	3.7
1817	26.2	1849	19.9	1881	-6.4
1818	8.8	1850	-2.1	1882	19.6
1819	-1.4	1851	-0.1	1883	-20.5

1884	5.0	1923	-6.5	1962	11.7
1885	-9.6	1924	-6.3	1963	-19.9
1886	-19.6	1925	15.8	1964	-7.9
1887	-10.9	1926	-5.5	1965	-2.4
1888	-18.4	1927	-0.2	1966	-10.4
1889	-0.2	1928	-12.8	1967	11.4
1890	-0.1	1929	-24.7	1968	8.7
1891	-5.6	1930	-5.2	1969	-27.4
1892	-6.0	1931	-9.6	1970	-22.8
1893	-6.7	1932	7.8	1971	-2.9
1894	16.3	1933	-9.7	1972	-31.4
1895	-14.4	1934	4.5	1973	3.2
1896	3.3	1935	-1.3	1974	-8.7
1897	-14.4	1936	-8.1	1975	13.7
1898	15.9	1937	-13.2	1976	5.2
1899	16.1	1938	11.7	1977	-12.9
1900	-19.1	1939	-1.6	1978	-7.8
1901	-7.9	1940	-15.9	1979	-16.4
1902	6.4	1941	-24.2	1980	-25.9
1903	21.7	1942	-23.2	1981	13.8
1904	-16.8	1943	11.5	1982	-6.1
1905	8.8	1944	20.6	1983	25.3
1906	16.9	1945	3.9	1984	-2.1
1907	4.2	1946	1.3	1985	-19.4
1908	-0.1	1947	-37.0	1986	-15.8
1909	-8.3	1948	-2.2	1987	-15.3
1910	11.0	1949	16.6	1988	8.3
1911	8.6	1950	1.7	1989	36.4
1912	-10.0	1951	-21.3	1990	39.9
1913	12.0	1952	9.9	1991	-9.9
1914	16.7	1953	-1.4	1992	18.3
1915	-10.2	1954	-20.2	1993	14.6
1916	2.6	1955	-0.7	1994	-0.6
1917	-18.9	1956	-1.7	1995	25.2
1918	0.6	1957	0.0	1996	-35.9
1919	-17.1	1958	6.1	1997	5.5
1920	10.8	1959	5.0	1998	15.9
1921	10.0	1960	-23.1	1999	11.9
1922	3.6	1961	4.2	2000	27.0

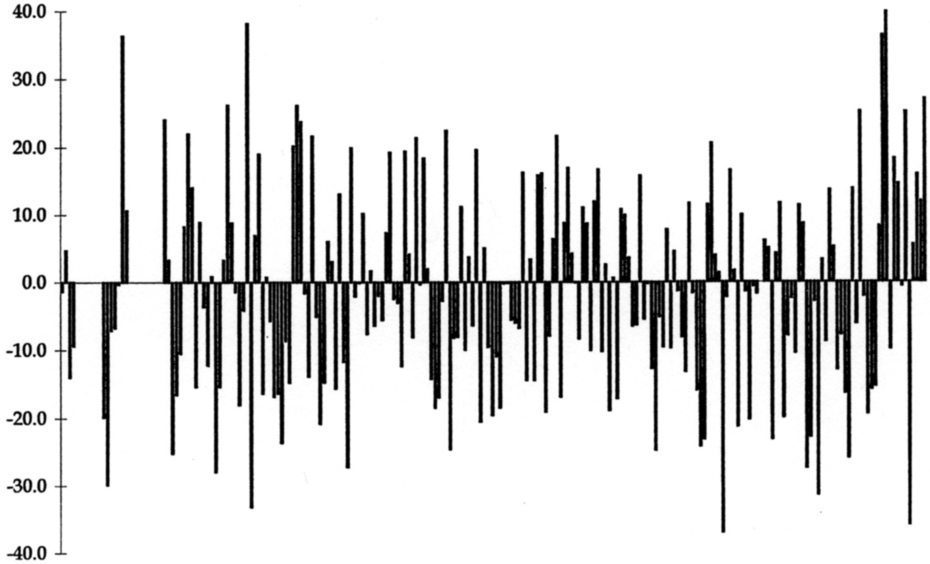


Figure 5-8. The inter-winter sea level oscillation (winter sea level deviations, cm) at Stockholm 1774 – 2000; data according to Table 5-3 (Ekman, 2003).

$$\Delta H = 4.17 \Delta p_N - 12.5 \qquad (5\text{-}2)$$

or inversely

$$\Delta p_N = 0.240 \Delta H + 3.0 \qquad (5\text{-}3)$$

Formula (5-2) tells us that an average air pressure difference across the North Sea of e.g. 15 hPa, as illustrated in Figure 5-10, will cause a long-term sea level in the Baltic Sea at Stockholm of 50 cm above normal. This is typically a maximum monthly mean sea level during an extreme winter; the highest monthly mean sea level observed is 54 cm (March 1990), the lowest - 51 cm (February 1947). Formula (5-3) can be used to estimate the south-north air pressure distribution over the North Sea and northern Europe for any winter all the way back to 1774. As an example we have done so for the extreme winters of Table 5-4; see Table 5-5.

From Tables 5-4 and 5-5 it appears that extreme values of the winter sea level only occur at the beginning and the end of the time period

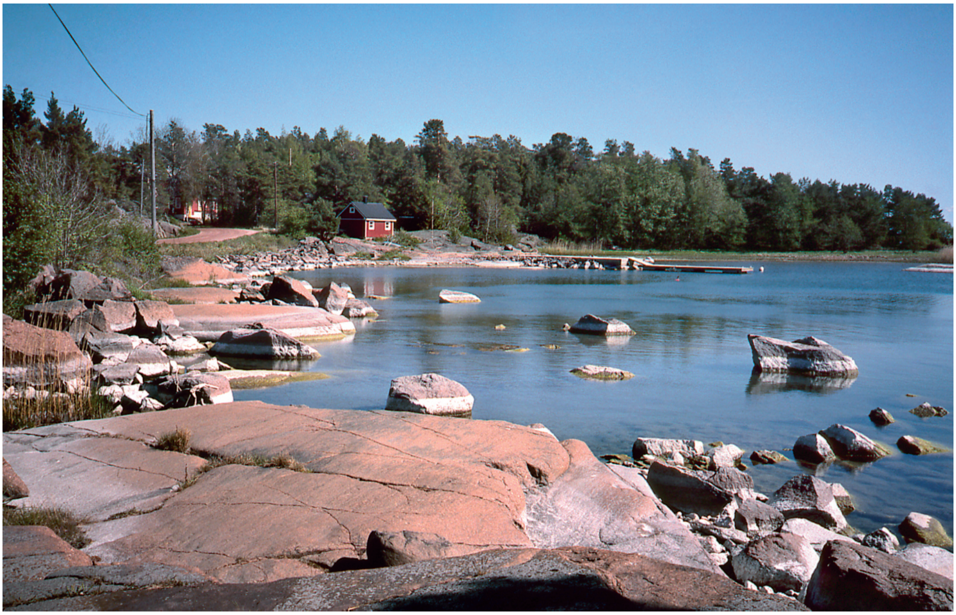


Figure 5-9. Low sea level during spring following a high sea level during winter, as shown by horizontal lines on rocks. This is due to a shift of the persistent wind field from west to east (Åland archipelago).

1774 – 2000. Also from Table 5-3 and Figure 5-8 one gets the impression that large positive or negative values are more frequent at the two ends of the time period. This calls for a closer investigation, performed by Ekman (2003). There the whole time period has been divided into three subperiods: one early period of about 60 years, 1774 – 1840, one central period of 100 years, 1841 – 1940, and one late period of 60 years, 1941 – 2000. For each of these the standard deviation of the winter sea level is computed, resulting in 17.1 cm, 12.3 cm and 17.3 cm for the three subperiods, respectively. This indicates that the inter-winter sea level variability might be much smaller during the central period. Applying F-tests a clear result is obtained: The *decrease in the inter-winter sea level oscillation* from the early period 1774 – 1840 to the central period 1841 – 1940 is statistically significant at the 99 % level. The *increase in the inter-winter sea level oscillation* from the central period 1841 – 1940 to the late period 1941 – 2000 is also statistically significant at the 99 % level. Hence, both changes reveal *systematic changes in the winter atmospheric circulation pattern over northern Europe*.

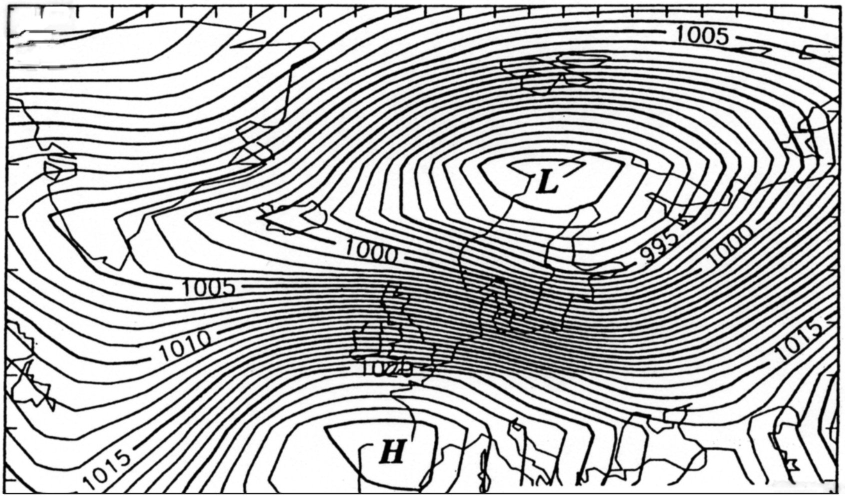


Figure 5-10. Typical air pressure distribution causing a large pressure difference across the North Sea. (Modified from Matthäus & Schinke, 1994.)

Table 5-4. Extreme winter mean sea levels (cm) according to Table 5-3 and corresponding main wind directions (Baltic entrance), temperature deviations (Stockholm, °C), and maximum ice extents (Baltic Sea, %).

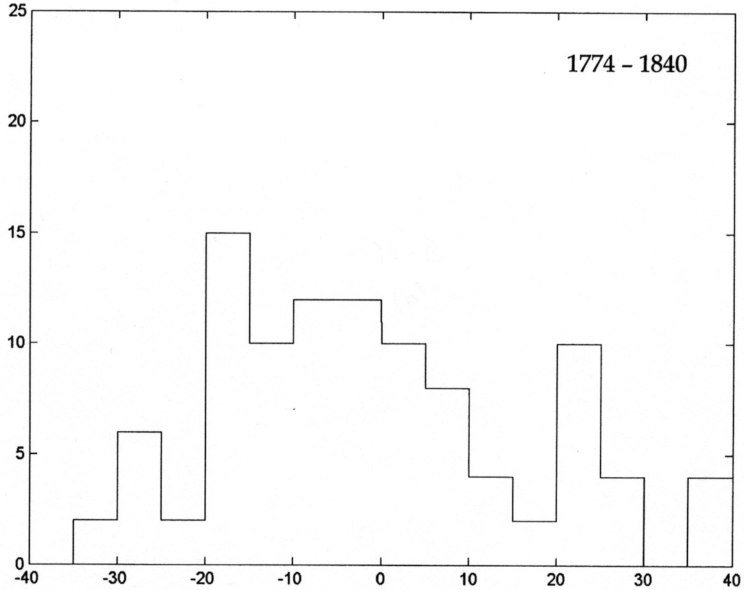
Year	Level	Wind	Temp.	Ice
1790	36.3	WSW	4.2	17
1822	38.2	WSW	4.9	18
1989	36.4	WSW	5.5	12
1990	39.9	SW	5.7	16
1823	-33.1	E	-0.5	43
1947	-37.0	ENE	-3.8	100
1996	-35.9	ENE	-1.1	62

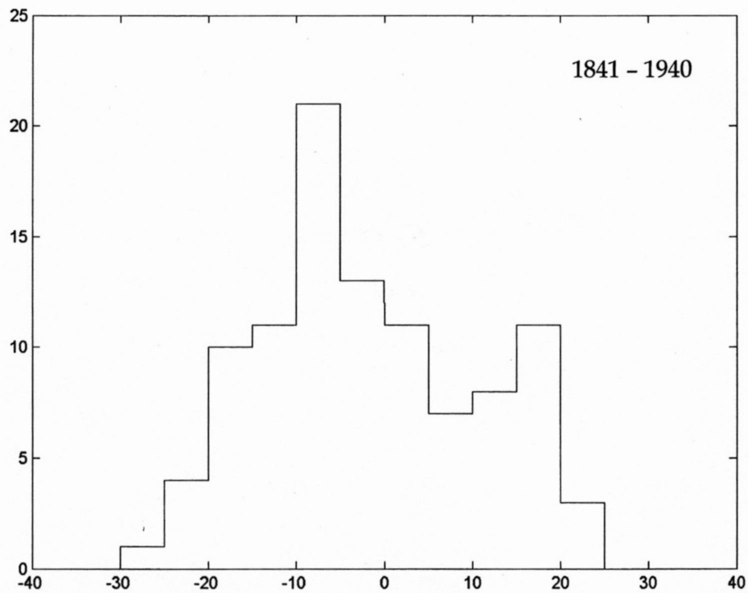
Table 5-5. Extreme winter mean sea levels (cm) according to Table 5-3 and corresponding estimated air pressure differences (hPa) across the North Sea (De Bilt – Oksøy). For the modern years the actually measured pressure differences (within brackets) are included as a comparison.

Year	Level	Pr. diff.	
1790	36.3	11.7	
1822	38.2	12.2	
1989	36.4	11.7	(10.5)
1990	39.9	12.6	(12.6)
1823	-33.1	-4.9	
1947	-37.0	-5.9	(-6.4)
1996	-35.9	-5.7	(-6.1)

It is interesting to make a graphical comparison of the distribution of the winter sea levels for the three time periods in question; see Figure 5-11, containing one diagram for each time period. This figure clearly shows the contrast between a more concentrated distribution during the central period (1841 – 1940) and a wider distribution during the early (1774 – 1840) and late (1941 – 2000) periods. The change in the variability produces a considerable change in the occurrence of extreme winters. As can be seen from the figures, the winter sea level deviation during the central period spans between approximately – 25 cm and + 25 cm, whereas it during the early and late periods spans between nearly – 40 cm and + 40 cm. Out of 19 winters with $|\Delta H| > 25$ cm thus only 1 has occurred during the central period, but 18 during the early and late periods.

Finally we note, as in Ekman (2003), that the modern extreme mild winter period starting in 1989, with dominating westerlies, is clearly reflected in the winter sea levels. While the average of the winter sea level deviations during the two hundred years 1774 – 1988 is - 2.3 cm, the average during the last 12 years, 1989 – 2000, is no less than 12.4 cm. It is noteworthy that a similar warm winter period seems to have occurred in


1774 – 1840


1841 – 1940

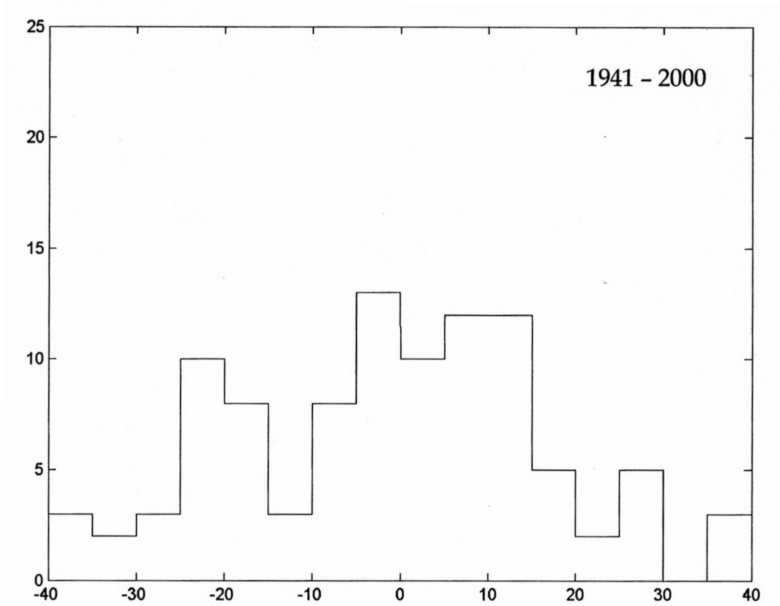


Figure 5-11. Distribution (percentage) of the winter sea level deviations (cm) for the time periods 1774 – 1840 (left above), 1841 – 1940 (left below), and 1941 – 2000 (above), respectively. The changing distribution reflects systematic changes in the atmospheric circulation pattern between the periods.

the beginning of the 1700s (Bergström & Ekman, 2002), recorded in the Uppsala temperature series and the ice break-up series of Lake Mälaren. This implies that the winter sea levels might have been equally high during the years 1715 – 1745, approximately.

5.7 Short-term sea level and another change in winter climate

There is another very long sea level series in the Baltic, that of Swinemünde (nowadays Świnoujście) on the south coast, commencing in 1811. Because of its position in the Baltic, this sea level station is considerably influenced by storms and gales, especially from north-east and south-west. Therefore, this sea level series should contain nearly 200 years of information on storm activity over the Baltic Sea.

Swinemünde is located fairly close to the left end in Figures 5-5 and 5-6, thereby being clearly affected by both long-term and short-term sea level variations. Hence, in order to extract storm information hidden in the sea level data the long-term variations have to be in some way eliminated. This has been done by Ekman (2007), concentrating on the winter season because the elimination of the long-term variations works better in winters and also because storms are more frequent during winters (and late autumns).

The quantity studied at Swinemünde is the short-term sea level effect in winters, being specified as the winter mean of the short-term sea level variations. It is calculated as the difference between winter mean sea level and normal sea level, from which is subtracted the winter mean of the long-term sea level variation. Winter mean sea level is defined as the average of the monthly means for January, February and March, as above for Stockholm (Section 5.6). Normal sea level is defined by two linear trends, one before 1865 representing a constant sea level and one after 1865 representing the global sea level rise occurring since the late 1800s; the inflexion point is fixed at the same year as at Stockholm above. The winter mean of the long-term sea level variation is the same quantity as at Stockholm but scaled down by a factor. This factor can be determined from Table 5-2 and Figure 5-7; they show that long-term sea level variations at Swinemünde are 0.140/0.196 = 0.71 times those at Stockholm. The factor itself has been stable over time.

The common time period for Swinemünde and Stockholm starts in 1811. However, as mentioned in Chapter 1 (Section 1.3) most of the Stockholm data for the years 1812 – 1824 have been transformed from København to fill a gap in the Stockholm series. Because of this, data from 1825 onwards have been used. The resultant numerical values of the short-term sea level effect for the winters since then are graphically illustrated in Figure 5-12. Large positive values mean frequent high sea levels, mostly depending on strong temporary northerly to easterly winds over the Baltic. Large negative values mean frequent low sea levels, mostly depending on strong temporary southerly to westerly winds over the same area.

Figure 5-12 reveals a tendency of larger values – both positive and negative – of the short-term sea level effect during the 1800s and smaller values during the 1900s. This calls for a closer investigation, performed by Ekman (2007). There the whole time period has been divided into two

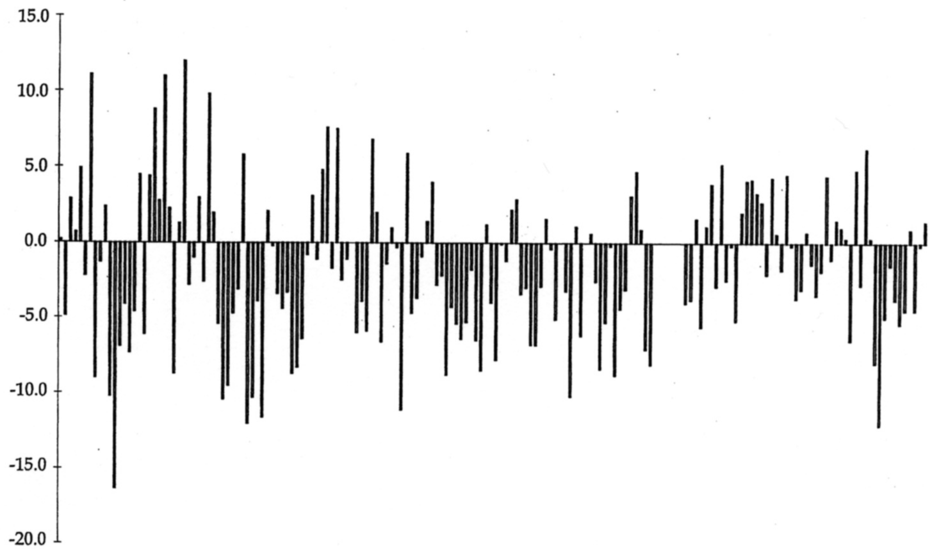


Figure 5-12. Short-term winter sea level effect (storm effect, cm) at Swinemünde 1825 – 2000 (Ekman, 2007).

subperiods, one for each century, i.e. one for 1825 – 1899 and one for 1900 – 1999. For each of these the standard deviation of the short-term sea level effect is computed, resulting in 6.0 cm for the first subperiod and 4.0 cm for the second one. This indicates that the variability of the short-term sea level effect might have decreased. Partial comparisons with the neighbour station Kolberg confirm these findings from Swinemünde. Applying an F-test a clear result is obtained: The *decrease in variability of the short-term sea level effect* from the 1800s to the 1900s is highly statistically significant, at the level of 99.9 %. This reveals a systematic change in the short-term sea level variations of the Baltic and, hence, a corresponding change in the short-term wind conditions.

The main conclusion in terms of winds, therefore, is that the *storm (and gale) activity during winters over the Baltic Sea has decreased* from the 1800s to the 1900s. This decrease is more pronounced in storms from around north-east (positive bars in Figure 5-12), and less pronounced in storms from around south-west (negative bars in Figure 5-12).

6. Pole tides and the rotation of the Earth – and the atmosphere once again

6.1 The discovery of polar motion

All the sea level phenomena we have dealt with hitherto have been observed before they have been explained theoretically. Now we come to a phenomenon that was predicted theoretically before it was observed.

It all started in 1844 when the German astronomer Christian August Friedrich Peters, working at the Russian central observatory of Pulkovo outside St. Petersburg, began to look for a periodic variation in its latitude. The background was that, according to Euler's theory for the rotation of rigid bodies, the axis of rotation in a freely rotating body is not stable, unless the axis of rotation coincides with an axis of symmetry of the body. Applying the theory to the Earth, which is somewhat flattened at the poles, Peters (1844) found that its rotational axis should move around its symmetry axis with a period of 304 days, close to 10 months. This means that each pole of the Earth should move around in a small circle of unknown radius with this period. If so, such a *polar motion* would manifest itself as a periodic variation of the latitude with the same period.

Peters started searching for a polar motion with the predicted period of 304 days. He did not find any. His successors continued searching. They did not find any either. Still after half a century the polar motion had not been detected.

Then, suddenly, a polar motion was discovered by the American insurance mathematician and private astronomer Seth Carlo Chandler (1891), reanalysing all the data. The amplitude was of the order of 10 m. But the period was not at all the predicted one – it was 427 days, close to 14 months. This was so contradictory to theory that many found it hard to believe. During fifty years scientists had tried to find the polar motion, with no result. And then one man succeeded, using the same data which had led nowhere when in the hands of others. How could this come about? The answer is that people before Chandler were so convinced about the theoretical 10-month-period that they never looked for anything else. Chandler, on the other hand, did not have the same respect for existing theories, and looked for any periodicity. But what could be the cause of such an unexpected 14-month-period?

Already the year after Chandler's discovery the American astronomer Simon Newcomb (1892) presented an explanation of the surprisingly long period of the polar motion. Newcomb writes:

"Mr. Chandler's discovery gives rise to the question whether there can be any defect in the theory which assigns 306 days as the time of rotation. The object of this paper is to point out that there is such a defect – namely, the failure to take account of the elasticity of the Earth itself, and of the mobility of the ocean."

From the knowledge of earth tides it was known that the Earth was somewhat elastic. Based on this Newcomb shows, with a fairly simple line of reasoning, that the effect of elasticity is to lengthen the period of polar motion by about 100 days. Furthermore, he realized that the polar motion, through the variation in latitude, will cause a corresponding variation in the centrifugal force of the Earth and, thereby, also in the level of the world's oceans. This variation, known as the *pole tide*, would be of the order of 1 cm at mid latitudes. In spite of its smallness Newcomb finds that it will lengthen the period of polar motion by some 30 days. Putting the two effects together he arrives at a theoretical period of 443 days, only slightly exceeding the observed period of 427 days. (The remaining discrepancy later turned out to be due to the liquid core of the Earth.)

Thus a hitherto unknown sea level phenomenon had now been predicted by Newcomb: a pole tide of period 14 months. It should be so small that it could only be expected to be detected with great difficulty. On the other hand, it was capable of lengthening the period of polar motion by one whole month. Therefore a considerable interest arose in trying to find the pole tide.

6.2 The search for the pole tide – and the surprising result

Two years after Newcomb's prediction of the pole tide the first analysis of sea level observations in this respect was published. It used 38 years of data from a sea level station on the North Sea coast of the Netherlands and was performed by the Dutch astronomer Hendricus Gerardus van de Sande Bakhuyzen (1894). He found indications of a pole tide of the predicted period and an amplitude of 1 cm. However, its phase was not in agreement with that of the polar motion, but this could, according to him, be ascribed to the uncertainty in the observations. Soon also the American hydrographer Alexander Smith Christie (1895) reported similar results from his coast of the Atlantic.

A closer look at the situation was taken by the German geophysicist Erich Przybyllok (1919). He analyzed data from German stations in the Baltic Sea as well as in the North Sea, most of them with long records, and in addition some Danish stations with shorter records. There was again a 14-month-variation with an amplitude of 1 cm. However, the amplitude hardly exceeded the standard error. Even worse, the phase was not at all in accordance with that of the polar motion. This led Przybyllok to a conjecture: Perhaps the observed effect, if it was there, was a meteorological one, connected to air pressure and winds.

After that, nothing new was reported in this field for a generation, not until the subject was taken up again by the American geophysicists Richard Haubrich and Walter Munk (1959). They made a spectral analysis of 11 sea level stations spread all over the world, all of them with records of about half a century or longer. A spectral peak at the pole tide frequency 0.84 cycles per year, corresponding to the period 14 months, was clearly seen for the stations in the Baltic Sea and the North Sea (and also for a Mediterranean station). For the other stations the pole tide peak was not above noise level. Thus the surprising and puzzling conclusion was that, while the pole tide in general could not be discovered, it could be discovered in the Baltic and North Seas. Moreover, there it was found to be considerably larger than predicted according to equilibrium theory. Another puzzling thing was that the Baltic station, Swinemünde, having the longest record, did not show a pole tide above noise level for the earlier part of the record but only for the later part. Some years later the Russian oceanographers Igor Maksimov and Valerii Karklin (1965) confirmed an enhanced pole tide in the rest of the Baltic Sea.

The special character of the Baltic Sea and the North Sea in the case of the pole tide clearly stands out in the more systematic investigation performed by the American oceanographers Stephen Miller and Carl Wunsch (1973). They applied Fourier analysis to a large number of sea level stations with reasonably long records all over the world, and then to a large number of stations restricted to the North Sea and the Baltic Sea. The world-wide analyses hardly resulted in any station with a pole tide above noise level. The North Sea and Baltic Sea analyses, on the other hand, gave a completely different result:

"The amplitudes are substantially above the background noise level, and rise markedly as one progresses from the North Sea into the Baltic and the Gulf of Bothnia."

The pole tide amplitude in the Baltic Sea reaches 3 cm, corresponding to no less than 6 times the predicted equilibrium amplitude.

Miller & Wunsch in their investigation also discovered a remarkable relation between the pole tide and the noise level:

"Across the shallow seas of northern Europe, the behaviour of both the low frequency sea level noise continuum and the annual peak is quite similar to that of the pole tide, suggesting that common factors may be locally at work on all sea level fluctuations at very low frequency."

Knowing of the results of Bergsten and others in Chapter 5 one should be tempted here to suggest that these common factors are meteorological – remember also the conjecture of Przybyllok above – but Miller & Wunsch do not do that. Instead they enter another road, suggesting that perhaps the enhanced pole tide might be due to resonance phenomena.

By now, the existence of the pole tide had been firmly established. However, it had turned out to be, in front of all, a Baltic Sea phenomenon. The reason for this was hidden in the dark, but there might be two different possibilities:

1. The pole tide in the Baltic Sea (and the North Sea) is caused by polar motion, and is enhanced due to some kind of resonance.

2. The pole tide in the Baltic Sea (and the North Sea) is to a minor degree caused by polar motion, and to a major degree by unknown meteorological effects of the same period.

6.3 Polar motion or winds?

It is well known that periodical variations of the sea level in certain cases may be considerably amplified through resonance. Whether resonance for a certain period will occur depends on the ratio between depth and size of the sea basin; normal resonance periods tend to be of the order of one day. Obviously the enhanced pole tide in the Baltic and North Seas, with a period of several hundred days, cannot be explained by such a resonance.

In spite of this, attempts have been made to find a polar motion resonance phenomenon to explain the pole tide observations. Including certain rotational effects on the ocean through the Coriolis parameter, Wunsch (1967) tried to develop a resonance theory that would explain the large pole tide in the North Sea. However, the observational results of Miller & Wunsch turned out to be in disagreement with the theory. To overcome this, Wunsch (1986) developed a more complex resonance theory. This was capable of giving a crude agreement with the observations.

Meanwhile, the Japanese astronomer Isao Naito (1977) – like Przybyllok half a century earlier – had started to doubt the connection between the observed pole tide and the polar motion. The reason for his doubt was his studies of temporal changes of amplitude and phase of the pole tide in the Baltic Sea and the North Sea. These observed changes did not correspond to the observed changes of amplitude and phase of the polar motion. Naito concluded that there must be, in addition to the polar motion, some unknown forcing with the same period to produce the observed pole tide.

Such an unknown forcing could be a meteorological one. It was known that there was a slight variation in the air pressure with a period of 14 months. The American geophysicist William O'Connor (1986) now assumed a 14-month-variation in the west-east wind stress over the North Sea and tried to estimate the resultant sea level variations. In this way he was able to reproduce some of the characteristics of the North Sea pole tide. This pointed to winds being responsible for the enhancement of the pole tide.

As has been noted before, the sea level in Stockholm may be said to represent the long-term behaviour of the whole Baltic Sea and the adjacent part of the North Sea. Applying Fourier analysis to the Stockholm series for the years 1825 – 1984, the author and his oceanographic colleague Anders Stigebrandt (Ekman & Stigebrandt, 1990) studied the amplitude of the pole tide during the last two centuries. For the first half of the time period the amplitude was below noise level, or below 2 cm. For the second half of the time period the amplitude was 3 cm. Thus the pole tide amplitude has increased, reaching above noise level; see Figure 6-1. The authors conclude two things: First, this contradicts resonance as an amplifying mechanism, since that would require a change in the topography of the area. Second, it supports a meteorological forcing, since that might have changed due to a small climatic shift.

An operational numerical tide and wind surge model for the North Sea was adopted by the Greek and British oceanographers Mikis Tsimplis, Roger Flather and Ian Vassie (1994) to study the mechanism of the pole tide there. Based on real weather data the model was used to predict monthly mean sea levels along the North Sea coast for a 30-year-period. These were then compared with observed monthly mean sea levels. It turned out that most of the observed pole tide was reproduced by the model, and that the west-east wind stress component provided the meteorological forcing. Hence their investigation provided a quite conclusive answer to the puzzling question on the origin of the large pole tide in the North Sea and, thereby, also in the co-oscillating Baltic Sea.

A confirmation of this concerning the Baltic Sea was given by the author (Ekman, 1996a), showing that the geographical pattern of the amplitude of the pole tide in the Baltic and adjacent waters is identical to the patterns of the mainly wind-driven seasonal and interannual variations there. Thus also the pole tide pattern is given by Figure 5-7 in Chapter 5.

Let us summarize the situation concerning the pole tide, or the 14-month-tide, in the Baltic Sea:

1. The pole tide in the Baltic Sea (and the North Sea) is to a minor degree caused by *polar motion*; this is the equilibrium tide.

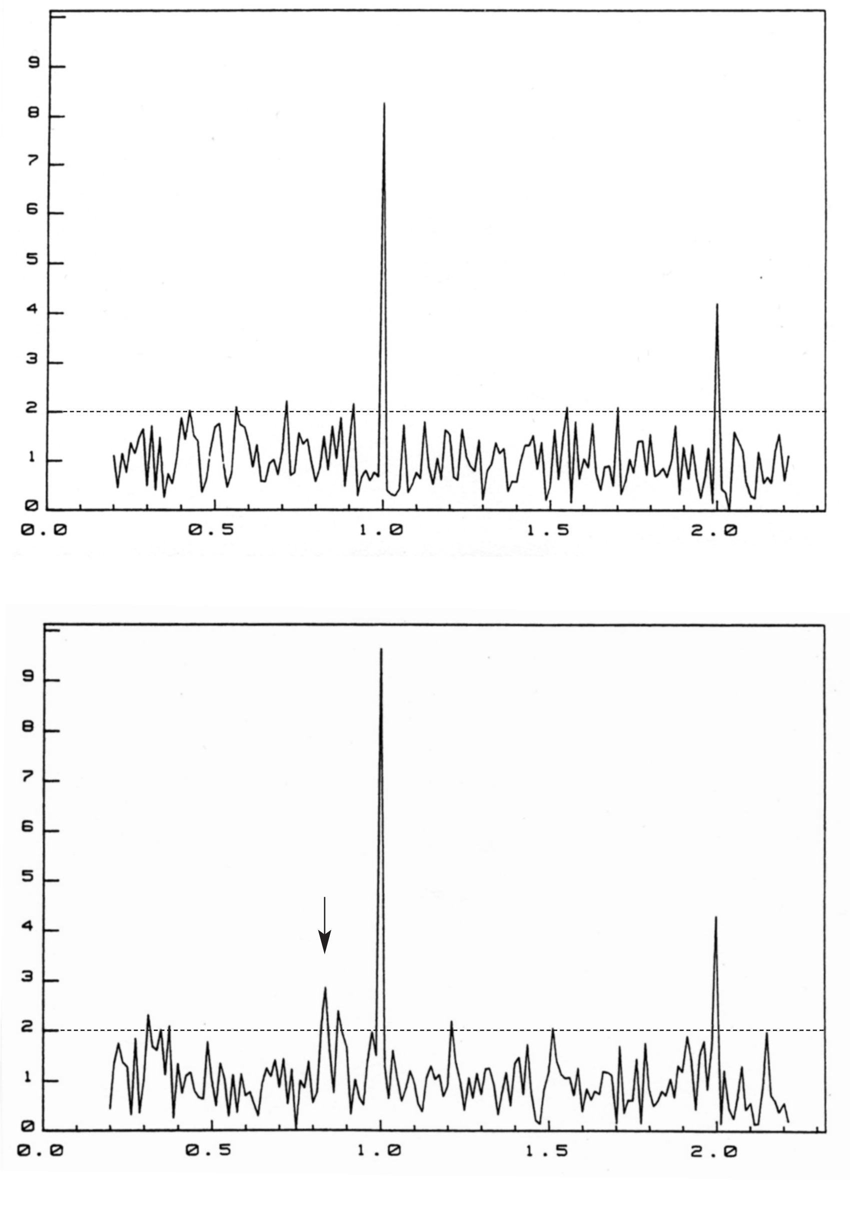


Figure 6-1. Spectrum of sea level amplitudes at Stockholm (cm) versus frequency (cycles/yr) for the time periods 1825 – 1904 (above) and 1905 – 1984 (below). In the first case the pole tide is below noise level, in the second case the pole tide is above noise level (Ekman & Stigebrandt, 1990).

2. The pole tide in the Baltic Sea (and the North Sea) is, at least during the last century, to a major degree caused by a small *variation in the atmospheric circulation* over the North Sea area.

Why, then, is there a 14-month-variation in the atmospheric circulation? That is a question still awaiting its answer.

7. Mean sea level and the sea water itself

7.1 At what height above sea level is sea level?

When we talk about a point having a certain height above sea level, what do we actually mean by ”sea level”? What is meant is the following. At some sea level station on the coast, sea level is measured during many years. The average of all observations constitute mean sea level, or normal sea level. In most of the Baltic Sea area, however, where postglacial uplift is going on, it is necessary to determine a trend line and then adopt the level of the trend line for a certain year as normal sea level. This is the zero point of the height system. The zero level in general is then that surface which passes through the zero point and is everywhere perpendicular to the plumb line, i.e. to the direction of gravity. This surface, the geoid, is an equipotential surface of the Earth’s gravity field, and is the one that is called ”sea level” in the expression height above sea level.

It could be mentioned here that originally zero points were defined nationally, around the Baltic Sea as mean sea level at Kronstadt (Russia), Helsinki (Finland), Stockholm (Sweden), Oslo (Norway), København (Denmark) and Swinemünde (Germany). Today in most cases a common zero point is used, based on mean high tide at Amsterdam as measured in 1684, nowadays closer to mean sea level because of the global sea level rise.

Now, an undisturbed water level, whether in a glass or in the sea, will always be perpendicular to the plumb line. Thus the mean sea level along a coast should be expected to coincide with the geoid and everywhere have the height zero. Whether this holds in reality should be possible to check by determining the height of the mean sea level along the coast. This can be done in the following way. Starting from the zero point, heights can be determined through so-called levelling for points on land all along the coast. Thereby, also the height of the vertical scale in a sea level station can be determined. When the height of the scale is known in this way, and the mean sea level on the scale is known from sea level observations, the height of the mean sea level can be determined.

In 1875 much of the German Baltic coast had been levelled. These levellings were extended to the sea level stations along the coast. When the German military geodesist Oskar Schreiber (1875) calculated the heights of the mean sea level for a number of stations along this coast, they did not come out as zero. In fact, it seemed as if mean sea level was lowest close to the Baltic entrance, and tended to increase in height with increasing distance eastwards from the Baltic entrance. This was the first indication of mean sea level perhaps being influenced also by other things than the gravity field.

Later on, with new and more accurate levellings, it became possible to make a more reliable determination of the deviation of the mean sea surface from the zero level. The German geodesist Alfred Westphal (1900) found that sea level in Swinemünde was about 6 cm higher than at Travemünde, Travemünde being close to the Baltic entrance and Swinemünde being some 200 km to the east of that. Since the standard error of the levelling between the two stations could be estimated at only 1 cm, the observed difference in sea surface height must be a real phenomenon. Westphal suggested that this could be an effect of the dominating westerly winds.

7.2 Mean sea surface topography and salinity of the sea water

At about the same time, national levellings were performed in most countries around the Baltic Sea. The Finnish oceanographer (and later foreign minister) Rolf Witting (1918) not only used these levellings to calculate the heights of mean sea level for a large number of sea level stations around the Baltic. He also developed an oceanographic model to explain this deviation of the mean sea level from the geoid, or the *mean sea surface topography*. Here *salinity* plays the major role.

Salinity affects the density of the sea water. Much salt yields a high density, implying a small volume and, thereby, a low mean sea level. Little salt yields a low density, implying a large volume and, thereby, a high mean sea level. In the Baltic Sea with its brackish water, salinity is highest at the entrance (Öresund and the Belts) and lowest at the northern end (Gulf of Bothnia). Consequently mean sea level should be low at the entrance and high in the north:

”The height of the sea level above the geoid increases pretty exactly in the length direction of the Baltic Sea; the inclination is largest in the Baltic entrance.”

According to Witting mean sea level should be almost 20 cm higher in the Gulf of Bothnia than at the Baltic entrance. Across the Baltic entrance there should be a further difference of some 10 cm. As mentioned the main cause would be differences in salinity (and temperature), but he also included a smaller atmospheric effect (air pressure and winds) in his model. The model was so accurate according to him that it clearly surpassed the accuracy of some of the national levellings. Hence the levellings could not be very much used to check the model; rather the model could be used to check the levellings.

After Witting’s work it came to a stand-still for half a century, until the Finnish oceanographer Eugenie Lisitzin (1965, 1974) took the subject up again. In connection with studying the global mean sea surface topography, she also studied the effect in the Baltic Sea. Her oceanographic model to a large extent may be said to confirm that of Witting.

By now, however, renewed national levellings were going on in the Nordic countries. Based on these when completed, together with sea level data, the author and his Finnish colleague Jaakko Mäkinen have performed a geodetic computation of the mean sea surface topography as well as comparisons with oceanographic models (Ekman & Mäkinen, 1996a).

The geodetic computation involved the creation of a consistent Nordic height system relevant for oceanographic purposes. This height system (Nordic Height system 1960, NH 60) not only has a common zero point (Amsterdam) but also a common treatment of the gravity field, the postglacial land uplift, the climatic sea level rise, and the so-called permanent earth tide. In addition, the system is strengthened by utilizing the geostrophic current in the Åland Sea to create a further connection between the Finnish and Swedish levellings. The resultant heights of the mean sea surface in this height system, at 42 reliable long-term sea level stations, are given in Table 7-1. The corresponding map of the mean sea surface topography is shown in Figure 7-1, covering both the Baltic Sea and its transition area to the North Sea.

Table 7-1. Heights of mean sea surface topography at sea level stations (cm). Stations are in anti-clockwise order around the Baltic and adjacent waters (and grouped by countries).

Station	Lat.	Long.	Height
Hamina	60 34	27 11	14.2
Helsinki	60 09	24 58	11.6
Hanko	59 49	22 58	12.3
Turku	60 25	22 06	13.3
Degerby (Åland)	60 02	20 23	13.2
Lemström (Åland)	60 06	20 01	13.4
Rauma	61 08	21 29	14.4
Mäntyluoto	61 36	21 29	14.9
Kaskinen	62 23	21 13	15.3
Vaasa	63 06	21 34	15.6
Pietarsaari	63 42	22 42	15.4
Raahe	64 42	24 30	16.6
Oulu	65 02	25 26	19.0
Kemi	65 44	24 33	20.5
Furuögrund	64 55	21 14	16.4
Ratan	64 00	20 55	16.7
Draghällan	62 20	17 28	(11.1)
Gävle	60 41	17 10	16.5
Björn	60 38	17 58	15.2
Stockholm	59 19	18 05	13.7
Södertälje	59 12	17 38	12.8
Landsort	58 45	17 52	10.6
Ölands norra udde	57 22	17 06	7.0
Kungsholmsfort	56 06	15 35	(1.0)
Ystad	55 25	13 49	4.5
Klagshamn	55 31	12 55	2.2
Varberg	57 06	12 13	- 1.4
Smögen	58 22	11 13	- 5.6

Oslo	59 54	10 45	1.8
Nevlunghavn	58 58	9 53	- 3.7
Tregde	58 00	7 34	- 9.0
Esbjerg	55 28	8 27	- 3.9
Hirtshals	57 36	9 57	- 13.7
Frederikshavn	57 26	10 34	- 11.1
Århus	56 09	10 13	- 9.0
Fredericia	55 34	9 46	- 8.7
Slipshavn	55 17	10 50	- 5.4
Korsør	55 20	11 08	- 2.8
Hornbæk	56 06	12 28	- 4.5
København	55 41	12 36	- 1.2
Gedser	54 34	11 58	- 1.1
Travemünde	53 58	10 52	- 6.0

Comparing their geodetic results with the model of Lisiztin (1965), Ekman & Mäkinen found statistically significant discrepancies. In short, her model was found to put too much sea surface topography in the Baltic and too little topography in the entrance to the Baltic.

At the same time new and improved oceanographic models have been developed by a group of Swedish oceanographers, for the Baltic Sea itself by Madleine Carlsson (1998) and for the Skagerrak by Bo Gustafsson and Anders Stigebrandt (1996). For the Kattegat in between there is a model by Stigebrandt (1983). These models emphasize salinity as the main contributing factor to the mean sea surface topography, although including also temperature, air pressure and wind stress. Currents are in general small within the Baltic but of some importance in the border zones between the Baltic, the Kattegat and the Skagerrak.

The general agreement between the geodetic solution of Ekman & Mäkinen and these oceanographic models turns out to be excellent; the discrepancies rarely exceed 2 – 3 cm. Hence the mean sea surface topography in the Baltic Sea area to a dominating extent is caused by the *distribution of salinity*. There are two main characteristics of the sea surface topography as shown in Figure 7-1. First, there is a continuous increase of

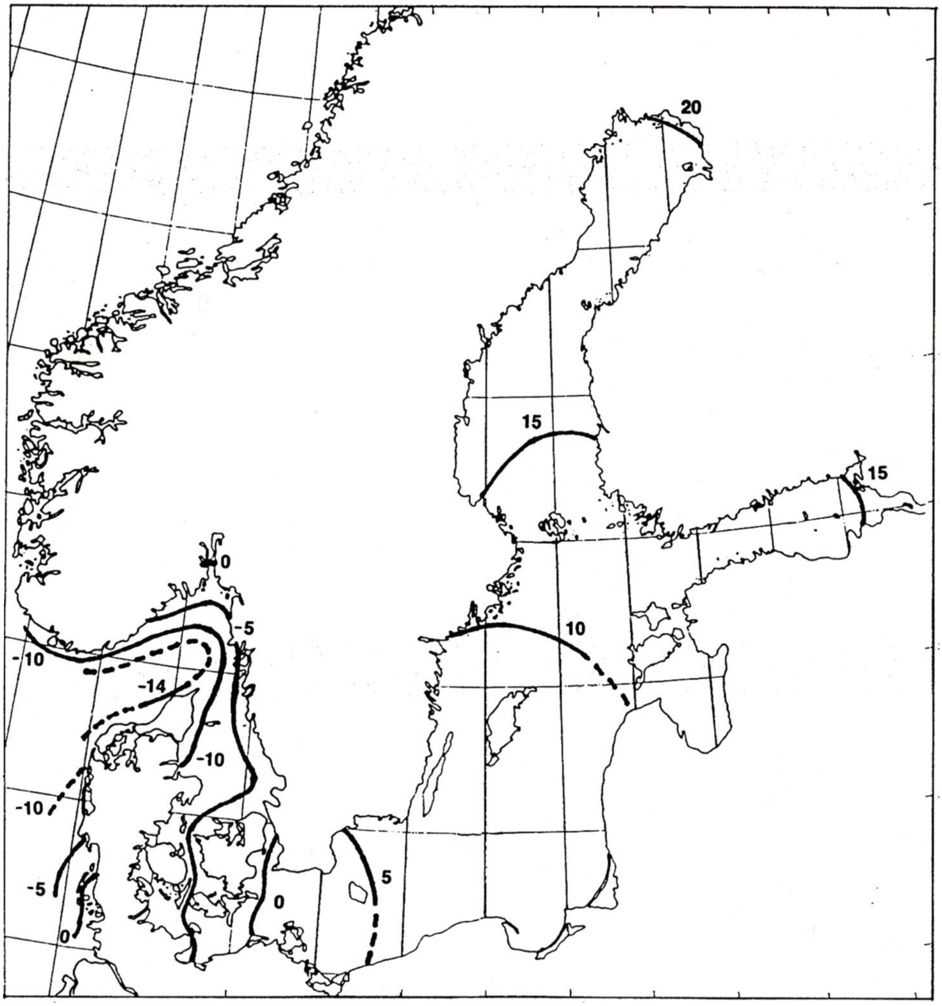


Figure 7-1. Mean sea surface topography (cm) in the Baltic Sea and its transition area to the North Sea, based on Table 7-1 (Ekman & Mäkinen, 1996a).

the sea surface height from the North Sea into the Baltic Sea, the height difference between the inner part of Gulf of Bothnia and the Skagerrak amounting to 35 – 40 cm. The main reason behind this is the considerable difference in salinity, close to the maximum possible one; compare also the high resolution model by the German geodesists and oceanographers Kristin Novotny, Gunter Liebsch, Reinhard Dietrich and Andreas Lehmann (2002). Second, there is a steep sea level gradient in the border zone between the Kattegat and the Skagerrak, reaching 2 cm per 10 km;

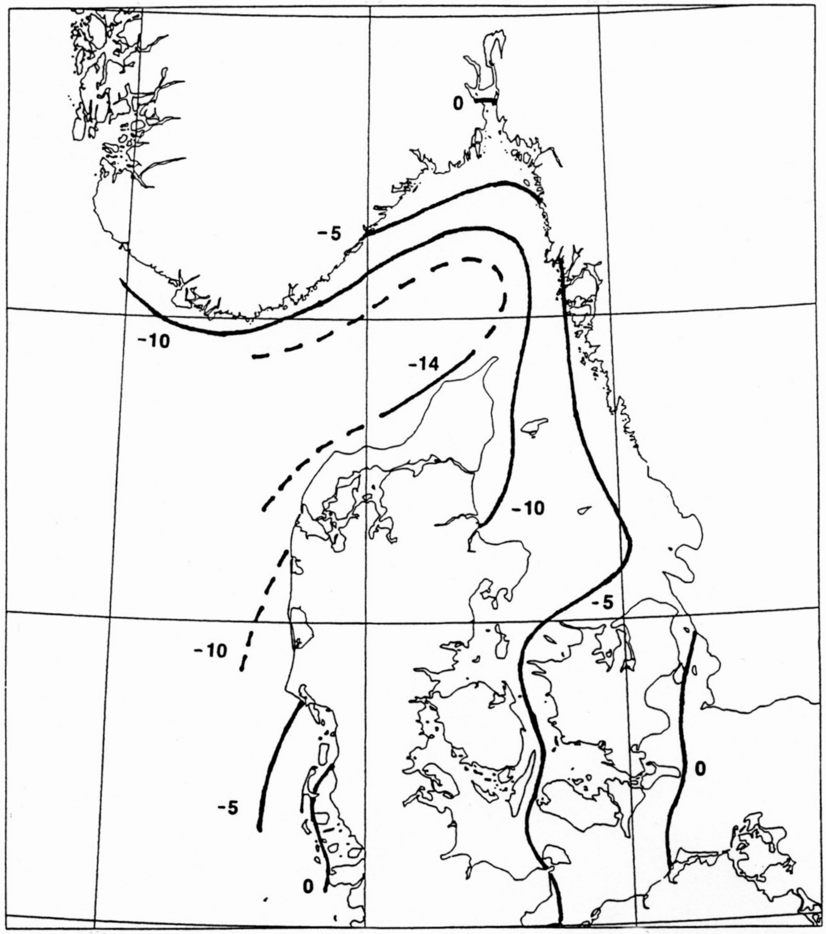


Figure 7-2. Mean sea surface topography (cm) in the transition area between the Baltic Sea and the North Sea. Detailed part of Figure 7-1.

see the detailed Figure 7-2. This reflects the salinity front there, separating the brackish Baltic Sea water from the saline North Sea water as illustrated in Figure 7-3, and the associated Baltic current. A local maximum in the sea surface can be seen in the Oslo Fiord, reflecting an accumulation of low-salinity water there.

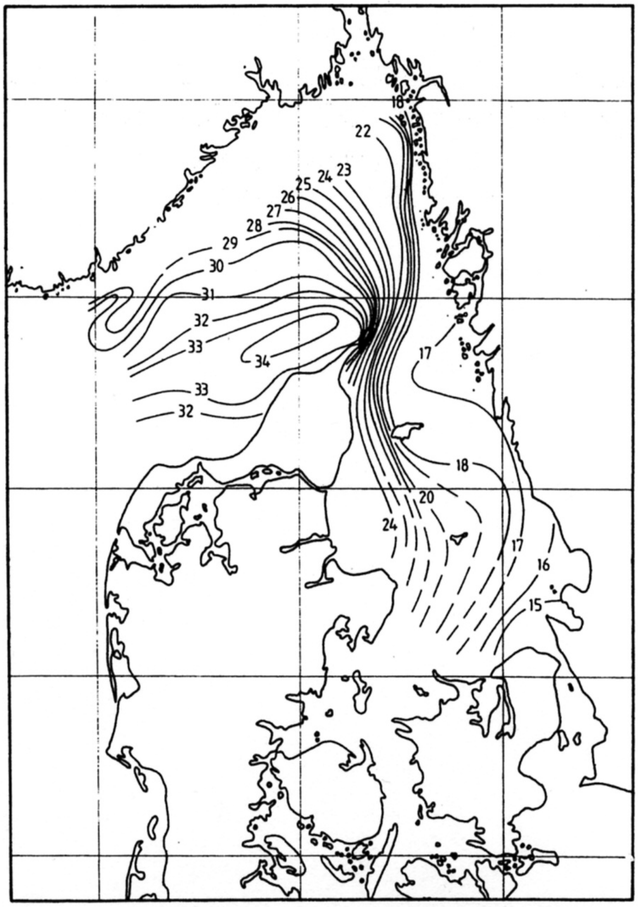


Figure 7-3. Typical surface salinity distribution in the border zone between Baltic Sea water and North Sea water. (From the Swedish Meteorological and Hydrological Institute.)

8. Some special effects

8.1 The world's oldest preserved sea level gauge

The original sea level scale of Stockholm, cut into the stone wall of the sluice, no longer exists. There is, however, another old sea level scale cut into stone that still exists, at Bomarsund on the Åland Islands in the middle of the Baltic Sea; see Figure 8-1. The Bomarsund sea level scale dates from 1837 (a part of it probably from 1822); it can be considered the oldest preserved sea level gauge in the world. The still existing mean sea level mark of 1731 cut into the Celsius rock at Lövgrund (Sections 1.2 and 2.3) is of course older, but that is not a complete sea level scale.

The background to the Bomarsund sea level scale is the establishment of a naval fortress. Åland, originally a part of Sweden, had, together with Finland, been ceded to Russia a few decades earlier. The Russians started erecting a huge fortress at Bomarsund, one of the purposes being to keep their Baltic naval fleet under protection there. In connection with the construction of the fortress, accurate depth measurements were performed in the surrounding shallow waters. In order to be able to relate the depths to normal sea level a stable sea level gauge was required, where the actual sea level could be measured.

The fortress was located on Åland mainly for military and political reasons, but also oceanographic aspects may have contributed. The Russian Baltic fleet had its base in Kronstadt at St. Petersburg in the innermost part of the Gulf of Finland, a place we know as strongly exposed to floods caused by south-westerly storms (Chapter 5). Bomarsund and Åland, being closer to the nodal line of the Baltic Sea, in this respect offered a much better location.

During the Crimean war, Great Britain and France attacked the Bomarsund fortress and blew it up. This lead to Åland being declared a demilitarized territory through an international convention of 1856 (a convention that was strengthened by the League of Nations later on, when also autonomy with legislation of its own was granted). The only thing that survived the demolition of the fortress was the sea level scale, which

Figure 8-1. The Bomarsund sea level scale on Åland, completed in 1837. Due to the postglacial land uplift there is no longer any sea water.

still can be seen at the water. However, not even the sea level scale can nowadays be possibly used. As it is carefully cut into a vertical part of the bedrock (and a stone erected on top of that) it has been continually rising due to the postglacial land uplift. The land uplift since the cutting of the sea level scale has been close to 1.0 m (Chapters 3 and 4), resulting in the sea level scale having lost its contact with the sea water. The scale made to measure the level of the sea now stands on dry land!

8.2 Saving a parliament from the postglacial uplift

Swedish democracy rests on an uncertain foundation. The foundation of its parliament building has to be saved – from lack of sea water due to the postglacial land uplift.

The Swedish parliament building in Stockholm is situated in the outlets of Lake Mälaren into the Baltic Sea. It is built on 15 000 wooden poles, all of them originally well below mean sea level. Because of the land uplift the wooden poles are gradually rising, approaching mean sea level. If nothing is done they will slowly be destroyed due to a reduction of protecting water.

When the parliament building was erected at the end of the 1800s the top plane of the wooden poles was found through levellings to be 0.64 m below mean sea level. Already at that time the leading state geodesist warned that the upper part of the wooden poles after about 100 years of land uplift would now and then lack water, and become more and more exposed to air.

The apparent land uplift at Stockholm during the last century has, according to Chapter 3 (Table 3-1), been 4.0 mm/yr. Consequently the wooden poles today should be only 0.20 m below mean sea level. During long-term low water in the Baltic Sea, due to persistent easterly winds, sea level may be 0.40 m below normal for a couple of months; see Chapter 5 (Table 5-3). During such periods the upper parts of the wooden poles will thus be above the protecting water.

Earlier Lake Mälaren, because of erosion of its outlets, behaved as a part of the Baltic Sea in connection with the land uplift. Nowadays, however, Lake Mälaren is artificially regulated through a barrage, making its level rise together with the land uplift. The parliament building, however, is situated on the Baltic side of the barrage.

In order to solve the problem, the barrage of Lake Mälaren has recently been extended to enclose also the parliament building. In other words, one has tried to move the building from the Baltic Sea to Lake Mälaren, so to speak. In this way it is expected that the water around the wooden poles will rise together with the land. Thereby, the parliament building might hopefully be saved from future destruction caused by postglacial land uplift.

8.3 Historical shore levels and Viking ship jetties

Postglacial land uplift causes the shore-line around the Baltic to fall continuously relative to the land. Consequently, in earlier times shore-lines were situated on higher levels and more inland. Using the knowledge of both the apparent land uplift and the climatic rise of sea level it is possible to calculate historical shore levels dating back in time to the Viking Age.

To start with, the rate of the apparent land uplift during the 1900s is well known along the coasts according to Chapter 3. However, from Chapter 4 it is clear that these rates are influenced by the ongoing climatic sea level rise. It is also clear that during the 1700s and 1800s this sea level rise was close to zero, and the apparent land uplift rates at that time about 1.0 mm/yr larger. Adding the knowledge we have of the global temperature during the last thousand years, we may state that the climatic sea level rise must have been close to zero during most of the last millennium. This means that apparent land uplift rates since the Viking Age in general have been 1.0 mm/yr larger than their values during the 1900s given in Chapter 3, at least as a long time average.

Let us now apply this to the remains of the Viking Age town of Birka west of Stockholm. Here Viking ship jetties dated to around the year 950 have been found at the approximate height 5.5 m above present mean sea level (2000). The apparent land uplift rate according to Table 3-1 and Figure 3-5 is 4.1 mm/yr, making it 5.1 mm/yr for the last millennium. Applying this we obtain a height of the Viking ship jetties of 5.2 m, agreeing well with the observed height. This confirms that the climatic sea level rise, on an average, should have been close to zero during the last millennium.

8.4 Sea level and the economy of the royal water mills

As was discussed in Chapter 5, persistent westerly winds over northern Europe cause a high long-term sea level in the Baltic Sea, sometimes causing the water in the outlet of Lake Mälaren to flow in the reverse direction, i.e. from the sea to the lake. In this outlet, close to the Royal Palace in Stockholm, there were long ago two large water mills, belonging to the Crown; one of them can be seen in the middle of Figure 5-1. They were operating on the condition that the water was running from the lake to the sea. When the water was running in the opposite direction, the water mills could not be used. This problem influenced the economy of the water mills.

In 1603 it was reported that the royal water mills gave almost no profit at all, because the water during much of the year was running in the wrong direction. Hence the level of the Baltic Sea must have been very high then. We may compare this with the later water level measurements at the Stockholm sluice: In 1854 the sea level was higher than the lake level for 137 days. During the second half of that year the sea level was higher for no less than 100 days. The year 1603 seems to have been at least as extreme as 1854. From this we conclude that large parts of the year 1603 must have been heavily dominated by westerly winds.

The royal water mills thus reveal interesting information about the Baltic Sea level and the atmospheric circulation over northern Europe during an extreme year in the beginning of the 1600s!

8.5 Sea level and the winter that never arrived

As was shown in Chapter 5, the Stockholm sea level series contain interesting information on winter climate. The most extreme winter mean sea level hitherto, as revealed by the Stockholm series, occurred in 1990, 40 cm above normal during the three months January – March. The second most extreme winter sea level, 38 cm, dates from 1822 (see Table 5-3). This year, however, the high sea level was not restricted to the three mentioned months but lasted for no less than five months, including the late autumn and early winter months at the end of the year before. During the period November 1821 – March 1822 the mean sea level was 36 cm above normal. In this respect the winter season 1821 – 1822 forms the most extreme one during the whole period 1774 – 2000.

Based on the winter mean sea level we should expect the winter 1821 – 1822 to stand out as exceptionally dominated by strong permanent westerly winds over northern Europe. This, in its turn should result in an exceptionally warm winter. This is confirmed by the few reliable temperature stations in northern Europe at that time, showing the winter temperature to be about 5° above normal.

Such a warm winter should cause a remarkably early ice break-up of lakes. In Lake Mälaren, for which the time of the ice break-up is known since the early 1700s, the ice break-up of 1822 occurred in the middle of March, no less than one and half month (43 days) earlier than normally.

As a result of the more or less permanently warm winter and westerly winds there should have been almost no snow but quite a lot of rain. This, in its turn, should have caused, contrary to normal, high flows in rivers during winter and lower flows during spring, the latter due to lack of ordinary melting away of snow. For the Memel River in Lithuania the water levels are known since the early 1800s. The water levels of 1822 compared to a normal year confirms our predictions: The maximum level was reached already in the beginning of February, as much as two months (60 days) earlier than normally.

On the other hand, in the Scandinavian mountains the effects should have been the opposite. The permanent and warm westerly winds should have promoted repeated heavy snowfalls over the Scandinavian mountain range close to the Atlantic coast, at least over its southern part in south-western Norway. This, in its turn, should have caused an unusually thick snow cover there during winter, followed by a considerable melting of snow with a high risk for extreme flows in rivers during spring. There are no systematic data of this kind available from that time, but it is recorded from the Dovre mountains that what normally was a small mountain brook in spring 1822 completely destroyed and swept away a farm with 17 houses, again confirming our predictions.

From the Åland Islands in the middle of the Baltic Sea there is a careful meteorological diary from the first half of the 1800s. It shows that the times of arrival of early migratory birds and blooming of early spring flowers were heavily affected in 1822. The recorded arrival of the skylark was a whole month (29 days) earlier than normal, as was also the blooming of the hepatica (33 days).

Now, due to the extremely warm air throughout the whole winter also the sea water of the Baltic must have been extremely warm during the winter of 1822. There are no known measurements of sea water temperature from that time, but the Ålandic meteorological diary also contains data on the spawning times of fish. In case of very warm water we should expect the spawning times to be affected. The most heavily affected species of fish was the burbot. However, the burbot reacted in the opposite way to what might be expected: Its spawning was delayed by a whole month (30 days late). Why did the burbot behave contradictory both to other fish and to flowers and birds? The background is that the burbot has its normal spawning time in winter, not in spring. So, while the others thought that spring was very early in 1822, the burbot had been waiting for a winter that never arrived.

It is noteworthy that all the different effects described above, stemming from different geographical locations, can be more or less predicted from observations of one single quantity at one single spot: the sea level at Stockholm!

Appendix: The Stockholm sea level series 1774 – 2000

Monthly and annual mean sea levels at Stockholm 1774 – 2000 (cm). For details see Section 1.3 and Ekman (2003). Also available as a computer file from the Permanent Service for Mean Sea Level (PSMSL).

	J	F	M	A	M	J	J	A	S	O	N	D	
1774	293	293	278	264	264	283	281	263	249	285	295	300	279.0
1775	298	281	302	308	308	295	290	307	312	305	307	296	300.8
1776	278	273	273	283	285	273	286	287	312	293	288	288	284.9
1777	277	277	283	278	280	273	300	306	311	285	322	303	291.3
1785	264	259	273	280	284	286	311	294	298	310	310	280	287.4
1786	252	261	251	246	260	283	*293*	*289*	*297*	*285*	*266*	*259*	*270.2*
1787	*274*	*286*	*270*	*269*	273	280	295	307	285	278	288	289	282.8
1788	*293*	*272*	*264*	267	277	283	285	294	282	291	299	303	284.2
1789	297	290	259	259	258	256	271	285	290	278	258	285	273.8
1790	318	331	305	251	234	269	294	292	312	292	275	295	289.0
1791	292	290	293	266	262	277	280	287	290	280	*268*	*280*	280.4
1801	303	303	299	281	266	283	293	272	273	258	293	302	285.5
1802	286	275	280	282	288	283	292	285	290	296	264	277	283.2
1803	235	253	266	271	280	294	278	274	297	287	277	275	273.9
1804	270	264	244	243	259	284	289	286	280	251	233	253	263.0
1805	264	256	274	238	244	288	280	275	288	273	269	306	271.3
1806	312	268	268	256	258	291	298	281	278	276	277	296	279.9
1807	309	299	279	266	270	280	293	273	290	291	291	294	286.3
1808	305	298	258	266	272	273	265	272	268	273	267	268	273.8
1809	245	260	266	251	261	281	276	268	270	271	276	269	266.2
1810	270	281	291	256	267	276	278	280	278	263	264	276	273.3
1811	263	268	272	268	261	269	271	280	276	272	272	305	273.1
1812	283	*248*	*245*	*250*	*246*	*256*	*276*	*274*	*277*	*280*	*281*	*275*	*265.9*
1813	*258*	*278*	*278*	*267*	*248*	*258*	*266*	*280*	*271*	*271*	*280*	*264*	*268.3*
1814	*271*	*234*	*222*	*237*	*239*	*245*	*261*	*259*	*262*	*258*	*265*	*280*	*252.8*
1815	*257*	*244*	*263*	*263*	*253*	*256*	*266*	*282*	*279*	*254*	*287*	*271*	*264.6*
1816	*275*	*281*	*263*	242	244	*255*	*252*	*280*	*270*	*276*	*273*	*277*	*265.7*
1817	*282*	*314*	*291*	*278*	*269*	*261*	*270*	*271*	*254*	*262*	*279*	*262*	*274.4*
1818	*279*	*275*	*280*	*266*	*245*	*260*	*277*	*274*	*269*	*247*	*256*	*263*	*265.9*

1819	*273*	*258*	*271*	266	242	*267*	*278*	*261*	*266*	*267*	258	240	*262.3*
1820	250	254	247	260	258	*260*	*276*	*283*	*275*	*270*	*261*	*260*	*262.8*
1821	*255*	*278*	*258*	*252*	*255*	*261*	*272*	*278*	*280*	*274*	*299*	*302*	*272.0*
1822	*309*	*296*	*311*	*274*	*251*	*270*	*277*	*277*	*285*	*265*	*272*	*260*	*278.9*
1823	*231*	*230*	*239*	*252*	*267*	*259*	*270*	*266*	*279*	*263*	*286*	*295*	*261.4*
1824	*287*	*271*	*260*	*241*	*265*	*255*	*276*	*276*	*264*	*267*	*301*	*312*	*272.9*
1825	308	291	253	266	251	267	270	272	273	278	306	266	275.1
1826	241	254	249	265	249	248	255	259	265	262	257	248	254.3
1827	275	248	270	253	239	245	273	272	258	241	262	274	259.2
1828	259	256	257	250	250	260	272	275	262	267	256	276	261.7
1829	243	240	254	237	253	250	266	262	265	265	270	236	253.4
1830	235	236	266	272	249	255	255	270	253	267	277	248	256.9
1831	246	238	230	226	248	250	250	251	252	254	284	267	249.7
1832	256	257	245	245	257	249	282	272	278	278	258	261	261.5
1833	255	258	226	234	248	259	262	279	267	246	274	304	259.3
1834	284	273	286	268	263	270	261	250	261	276	290	283	272.1
1835	287	299	274	266	255	258	266	265	241	253	255	278	266.4
1836	281	288	283	264	247	262	283	277	271	268	266	261	270.9
1837	266	253	256	241	246	246	258	262	254	259	287	266	257.8
1838	242	244	251	262	248	258	270	291	276	269	272	284	263.9
1839	304	280	258	259	261	265	269	277	272	263	241	217	263.8
1840	266	261	233	238	238	258	264	254	272	266	263	248	255.1
1841	240	235	236	236	247	266	265	264	242	256	261	270	251.5
1842	232	236	259	243	237	258	278	254	240	246	255	265	250.3
1843	284	263	240	240	220	240	262	253	253	272	261	279	255.6
1844	274	257	245	240	250	261	283	276	260	271	250	223	257.5
1845	240	242	236	240	235	240	250	252	257	269	267	281	250.8
1846	270	263	269	244	241	260	267	248	246	246	233	254	253.4
1847	232	252	242	240	235	247	247	242	262	249	268	259	247.9
1848	209	237	232	237	242	244	264	279	273	238	265	276	249.7
1849	253	285	280	224	221	262	270	266	249	248	262	224	253.7
1850	216	264	271	226	240	248	259	249	256	255	272	272	252.3
1851	265	250	241	233	242	271	268	257	253	255	265	260	255.0
1852	278	264	244	237	231	242	246	244	248	270	252	268	252.0
1853	276	232	224	226	234	231	256	265	252	264	250	233	245.3
1854	228	268	263	258	249	242	248	247	267	274	264	278	257.2
1855	276	226	232	240	240	232	240	257	258	263	241	253	246.5
1856	250	258	238	234	239	249	266	254	255	244	254	274	251.3
1857	256	237	241	214	221	238	259	252	239	251	235	266	242.4
1858	271	252	248	265	249	239	253	243	249	261	253	246	252.4
1859	257	265	283	270	232	237	257	258	254	246	255	244	254.8

1860	251	252	235	235	237	246	255	255	263	266	244	229	247.3
1861	234	245	255	237	263	237	244	272	270	239	248	261	250.4
1862	241	237	226	235	237	252	274	260	241	253	250	231	244.8
1863	262	288	247	246	248	244	261	267	264	254	267	276	260.3
1864	254	254	241	240	233	251	257	274	260	249	239	221	247.8
1865	257	233	222	226	236	254	250	251	256	235	250	249	243.3
1866	275	293	231	222	239	239	258	260	256	235	270	275	254.4
1867	249	256	228	249	226	243	258	251	243	256	272	265	249.7
1868	241	283	264	241	250	255	249	235	253	244	258	244	251.4
1869	237	265	236	221	235	251	252	254	262	268	278	251	250.8
1870	243	215	231	228	248	247	256	232	254	246	248	231	239.9
1871	228	207	241	252	236	236	238	253	240	230	232	242	236.3
1872	244	213	223	232	232	234	240	243	252	250	252	245	238.3
1873	262	235	225	215	239	242	248	255	252	262	252	285	247.7
1874	285	273	239	245	228	246	245	255	256	254	261	246	252.8
1875	224	225	206	228	238	243	233	231	238	230	221	223	228.3
1876	231	228	244	231	222	237	248	246	257	241	234	216	236.3
1877	220	244	238	221	223	233	251	253	255	251	265	245	241.6
1878	247	249	262	227	222	252	251	238	255	257	248	247	246.3
1879	240	220	233	213	223	237	254	243	250	253	252	238	238.0
1880	253	240	239	217	231	230	235	236	226	239	258	283	240.6
1881	256	224	220	228	229	237	243	260	240	226	235	241	236.6
1882	261	253	262	225	228	240	234	250	234	204	224	210	235.4
1883	217	213	224	213	219	233	238	250	243	242	254	264	234.2
1884	258	257	214	201	227	234	234	231	222	248	249	251	235.5
1885	223	225	236	214	219	241	235	238	245	249	230	254	234.1
1886	255	207	191	216	215	223	250	246	238	225	215	255	228.0
1887	220	227	231	225	226	232	240	250	243	245	238	260	236.4
1888	231	226	198	206	229	224	234	238	228	250	236	256	229.7
1889	235	253	221	220	206	222	238	256	243	234	230	231	232.4
1890	247	232	230	230	220	245	249	243	238	264	247	220	238.7
1891	220	232	240	210	222	220	231	245	244	240	226	243	231.1
1892	245	241	204	225	233	236	249	243	243	233	218	240	234.2
1893	222	223	243	234	219	235	232	242	263	260	261	252	240.4
1894	236	273	246	210	219	228	236	244	243	224	239	245	236.9
1895	231	207	224	234	215	221	246	244	253	252	246	238	234.2
1896	232	246	236	226	231	233	246	239	230	233	230	219	233.4
1897	210	225	223	226	227	227	242	234	242	239	226	242	230.2
1898	248	265	234	219	218	228	256	245	247	222	232	265	240.0
1899	263	242	242	243	222	233	226	244	252	254	268	251	245.0
1900	214	211	214	213	231	226	237	236	236	258	229	243	229.0

1901	229	234	209	218	205	226	222	225	218	226	238	247	224.6
1902	258	234	220	204	218	222	242	250	243	229	228	217	230.4
1903	239	269	249	253	230	223	239	261	254	236	244	229	243.6
1904	218	222	200	214	229	232	248	248	226	227	243	256	230.1
1905	249	255	212	218	221	217	239	246	244	244	223	246	234.4
1906	244	245	251	224	213	230	240	243	232	220	218	251	234.2
1907	236	226	240	218	228	223	238	258	251	225	208	215	230.3
1908	225	256	207	201	217	218	220	235	242	218	214	233	223.7
1909	229	228	205	208	219	228	240	252	234	229	239	234	228.8
1910	257	239	225	219	224	218	238	231	220	225	232	218	228.8
1911	240	239	233	221	221	216	236	226	247	231	248	221	231.6
1912	215	221	219	231	226	236	217	237	245	228	237	263	231.2
1913	238	228	254	228	211	233	236	241	214	211	248	279	235.2
1914	250	252	231	221	233	220	224	230	229	225	207	241	230.2
1915	222	214	215	225	221	226	232	239	238	204	216	235	223.9
1916	247	242	198	215	215	223	231	238	231	236	224	224	227.0
1917	214	207	200	219	214	212	218	215	236	249	246	266	224.8
1918	242	229	207	198	188	229	235	233	247	240	222	225	224.5
1919	218	205	200	217	202	227	233	252	237	240	202	228	221.7
1920	237	234	234	214	226	222	226	237	225	198	206	195	221.1
1921	241	230	229	228	210	227	239	239	238	240	231	232	232.0
1922	246	205	230	208	221	234	234	239	228	214	229	244	227.6
1923	237	227	185	186	216	241	235	249	240	252	260	235	230.3
1924	213	223	213	219	212	221	240	223	226	224	226	222	221.8
1925	256	245	214	211	204	227	220	230	244	240	228	232	229.2
1926	221	202	227	211	207	216	218	232	242	232	223	228	221.6
1927	235	219	211	225	233	237	227	228	232	241	236	202	227.2
1928	218	225	184	196	202	231	247	245	234	232	232	234	223.2
1929	211	181	199	213	214	226	235	227	232	243	233	233	220.4
1930	234	208	207	196	200	208	227	237	210	225	258	225	219.4
1931	227	201	206	204	203	219	234	226	229	236	224	225	219.6
1932	247	232	207	214	207	215	221	228	233	240	221	226	224.1
1933	211	221	199	224	207	202	222	238	216	209	210	199	213.3
1934	215	236	222	183	211	221	222	230	216	242	235	218	220.8
1935	206	235	213	221	200	213	234	232	228	247	228	229	223.7
1936	228	211	192	209	196	208	216	224	217	224	231	238	216.1
1937	222	193	199	194	200	210	225	219	228	212	218	208	210.6
1938	217	233	237	246	214	223	228	209	217	230	238	212	225.3
1939	207	230	209	207	196	213	222	211	195	189	197	217	207.7
1940	213	184	204	197	190	203	213	234	244	215	217	226	211.6
1941	190	187	198	189	191	200	213	222	226	211	195	223	203.7

1942	208	184	184	193	199	216	224	213	218	236	229	237	211.8
1943	215	238	227	235	221	216	226	235	220	225	215	219	224.3
1944	249	238	220	203	221	216	214	207	220	214	216	219	219.8
1945	221	210	225	228	215	224	226	224	213	222	209	222	219.8
1946	216	231	202	224	203	216	216	225	227	212	200	197	213.9
1947	180	164	189	215	196	204	211	205	204	222	218	220	202.3
1948	222	206	208	207	200	211	220	221	229	243	231	226	218.5
1949	237	237	218	213	213	222	218	234	203	214	218	239	222.0
1950	220	209	218	219	201	217	221	209	227	242	217	223	218.5
1951	208	181	187	210	195	196	218	209	210	192	194	250	204.1
1952	243	227	198	196	197	227	223	214	230	228	217	216	218.0
1953	204	220	208	213	200	204	214	232	234	219	210	218	214.7
1954	223	174	177	195	189	193	222	221	227	236	232	227	209.7
1955	221	214	196	201	220	207	207	202	214	226	223	244	214.5
1956	240	195	191	193	209	208	215	228	212	228	207	226	212.7
1957	212	222	195	191	201	206	213	219	231	238	224	223	214.6
1958	226	220	200	183	214	203	213	219	199	213	208	215	209.3
1959	232	207	202	203	188	208	209	203	212	204	198	177	203.6
1960	201	188	167	178	194	206	217	219	217	192	198	223	199.9
1961	197	211	229	220	207	222	238	234	223	200	219	221	218.4
1962	233	233	193	196	199	209	222	221	236	210	201	215	213.9
1963	192	188	184	175	186	190	207	207	202	230	220	210	199.1
1964	211	218	170	176	202	201	216	214	220	211	215	228	206.7
1965	216	206	193	192	186	195	223	215	212	203	217	213	205.8
1966	190	184	216	194	194	201	215	211	222	207	194	214	203.6
1967	216	202	237	219	205	206	210	215	210	232	227	235	217.7
1968	217	215	214	212	199	188	206	195	187	208	197	195	202.8
1969	183	189	164	192	189	193	210	191	206	217	249	202	198.8
1970	176	185	188	206	196	197	213	204	212	212	230	217	202.9
1971	205	208	195	187	186	192	214	201	207	218	232	231	206.2
1972	186	168	166	202	184	201	200	199	199	202	234	227	197.2
1973	196	219	208	215	196	199	205	207	209	199	228	238	209.8
1974	210	207	168	174	172	204	228	216	203	215	215	244	204.6
1975	252	208	190	191	190	198	197	202	204	207	193	220	204.2
1976	250	191	182	197	188	196	196	199	191	169	182	214	196.0
1977	193	183	192	201	191	191	212	191	204	204	235	202	199.8
1978	213	174	193	180	165	188	203	200	235	214	228	192	198.8
1979	178	186	190	175	192	186	221	208	218	199	198	217	197.3
1980	188	174	163	184	181	191	200	200	206	218	213	234	196.0
1981	234	224	186	181	183	201	207	212	196	214	236	234	208.9
1982	196	192	195	204	202	189	193	199	214	184	209	226	200.2

1983	253	223	200	194	183	193	200	200	210	233	234	215	211.4
1984	240	188	166	177	180	192	211	195	208	220	194	198	197.4
1985	182	187	173	187	183	196	204	205	220	210	214	208	197.3
1986	213	167	172	178	182	189	205	199	220	214	224	230	199.3
1987	187	198	168	175	192	194	201	213	216	199	199	205	195.4
1988	222	202	197	189	178	189	189	212	211	207	206	221	202.0
1989	237	246	221	192	199	194	200	214	198	211	206	212	210.8
1990	225	237	252	209	189	191	209	203	207	211	203	199	211.0
1991	212	179	171	181	183	200	201	203	203	203	199	207	195.3
1992	227	211	207	192	193	174	190	208	204	185	208	208	200.5
1993	218	220	194	178	170	195	212	209	190	171	169	195	193.4
1994	205	185	194	191	174	207	189	187	194	202	197	219	195.4
1995	217	228	215	216	192	192	194	187	184	203	208	175	200.8
1996	165	155	155	168	181	192	205	181	169	184	215	194	180.4
1997	184	208	206	207	190	185	179	179	208	218	190	180	194.5
1998	201	214	214	171	181	193	212	216	200	191	213	199	200.3
1999	209	214	192	192	180	183	188	189	181	200	190	228	195.7
2000	217	227	217	182	174	199	211	202	180	177	193	204	198.5

Figure A-1. The Stockholm sluice in the 1790s. The picture shows the part of the sluice where the sea level observations were made. (Coloured lithograph by F Verner 1824, based on a drawing from the 1790s by J P Cumelin.)

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Note: As explained in the preface the above reference list is not ordered alphabetically but chronologically.

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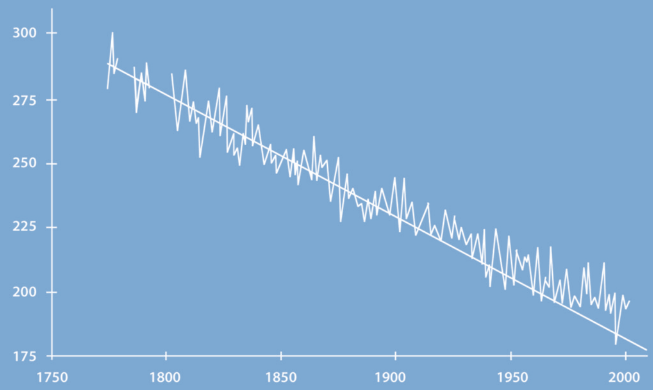

This is a book about the sea level of the Baltic Sea. It might seem as a very specialized subject. In fact it is not, on the contrary. The fascinating thing is that this single physical quantity – the Baltic Sea level – tells us a lot about the planet we live on. The Baltic Sea has the world's longest series of sea level observations. From the Baltic Sea level, as observed during three centuries, we are able to draw conclusions about the behaviour of our Earth: its interior, its oceans, and its atmosphere. Thus, historical data from the Baltic Sea are used to solve modern Earth science problems of a more global character. This is the fundamental idea of the book.

Moreover, the book gives a historical perspective on discoveries and solutions of the sea level problems. Things are explained by describing how they have actually been found out (or not found out), starting from the very beginning, sometimes commenting on old results from a modern point of view. Original scientific sources are used throughout. This means throwing light also on important works being long since forgotten by modern scientists.

Finally, in order to broaden the outlook in somewhat unexpected directions, some special aspects related to the sea level changes are included at the end of the book.

This book spans several Earth sciences, from solid geophysics through oceanography to climatology. It is intended for reading by a wide range of geoscientists or other people with a professional interest in the Earth and its changes. I hope you will find the book interesting.