Small Publications in Historical Geophysics

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Crustal Loading and Gravity Change during the Greatest Storm Flood in the Baltic Sea

Per-Anders Olsson & Martin Ekman

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1. Background

Sea level variations in the Baltic Sea are mainly due to winds. These affect the sea level in two different ways; see Ekman (2009). We illustrate this schematically in Figures 1 and 2.

Figure 1 shows what happens when a persistent wind from south-west or north-east is blowing over the North Sea and the Baltic entrance, say during a month. Sea water is transported into or out of the Baltic, depending on the direction of the wind, thereby raising or lowering the Baltic Sea level as a whole.

Figure 2 shows what happens when a temporary wind from south-west or north-east, say a storm, is blowing over the Baltic Sea. Water is then redistributed within the Baltic Sea, producing high or low sea levels at the ends of the Baltic depending on the direction of the wind. In the middle there is a nodal line with no variations at all.

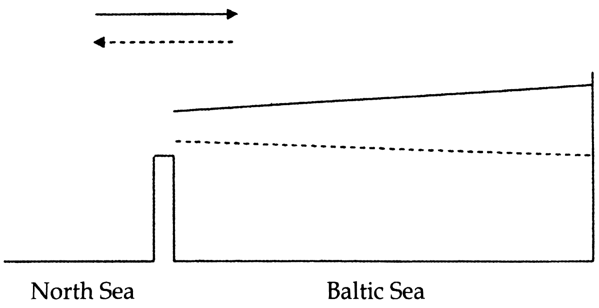

Figure 1. Long-term effect on the Baltic Sea level caused by a persistent wind from south-west (continuous line) or north-east (dashed line). (Ekman, 2009.)

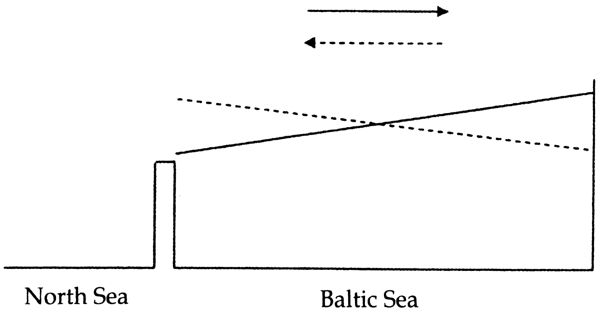

Figure 2. Short-term effect on the Baltic Sea level caused by a temporary wind from south-west (continuous line) or north-east (dashed line). (Ekman, 2009.)

During such a storm the additional water mass at the end of the Baltic will, through its loading on the crust, cause a vertical displacement of the crust. Moreover, this vertical displacement, together with the additional water mass itself, will cause a change in gravity. These phenomena will be the subjects of this publication. As the event to be investigated here is the greatest storm flood in the Baltic Sea, the results will represent realistic maximum effects in connection with such an event.

2. The storm flood of 1872

In 1872 a remarkable storm occurred over the Baltic Sea. It was not the most severe storm that had occurred. A storm in 1824 had caused the highest sea level ever observed in the Baltic, 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. Extensive coastal areas in both Germany and Denmark were flooded, whereby buildings were damaged all over, more than 100 people were drowned and more than 100 ships were stranded, some of them far inland. Thus there was a considerable interest in having this event scientifically examined.

In Germany 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. In Denmark Colding (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 velocity.

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 is proportional to the square of the wind velocity. Moreover, it is proportional to the length of the open sea over which the wind is blowing and inversely proportional to the depth of the sea.

Thus the sea level becomes especially high for very high wind velocities in combination with a large and shallow sea, like the Baltic 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. A nodal line was located somewhere in the middle of the Baltic Sea, going from Stockholm towards the south-eastern Baltic.

Finally Colding found that the storm caused a sea level difference of 3 m across the Baltic entrance, between the Baltic just to the south of the Öresund and 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.

All the sea level data were put together by Colding (1881) into a sea level map, showing the maximum deviation of the Baltic Sea level from normal during the storm; see Figure 3. This occurred in the early afternoon on 13 November 1872. The sea level heights on the original map are given in Danish

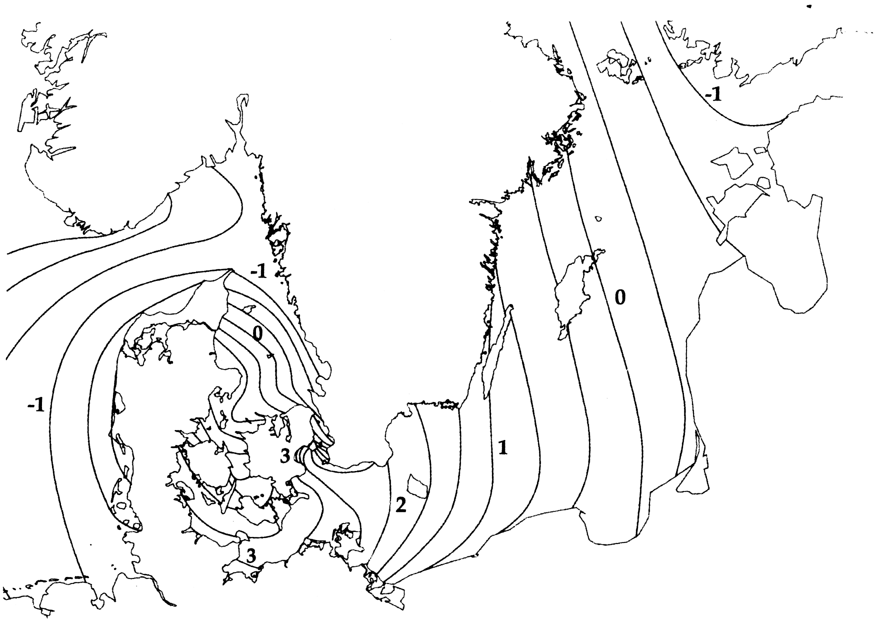

Figure 3. Sea level change (m) due to the north-easterly storm of 1872.
(Redrawn from Colding, 1881.)

feet (the Danish foot being equal to the Prussian foot used in northern Germany). They are here converted into m through the relation 1 Danish foot = 0.31385 m. This careful map of the sea level distribution during the storm allows some interesting investigations of the effects of the water load added.

3. Effects of an additional water load

The considerable water mass added in the south-western Baltic due to the storm causes a vertical displacement of the crust (sea bottom). The comparatively short duration of a phenomenon like this makes the response a completely elastic one. This is unlike for example the case with the ice load during the Ice Age where the resulting deformation mainly is viscous. An elastic vertical displacement can be numerically characterized by the so-called load Love numbers. In principle, for a point load the vertical displacement is the load Love number multiplied by the load itself (for each spherical harmonic degree). In our case, with a load having a fairly large extension, the vertical displacement has to be calculated as the integral of the above product over the load area; see further Farrell (1972).

In order to compute the vertical displacement we therefore need two things. First we need a sufficiently detailed knowledge of the height of the additional water load. This is provided by Colding (1881). Second we need a sufficiently detailed knowledge of the coast-line to define the area of integration.

The effect of the additional water on gravity is computed in a somewhat similar way as above. In this case, however, two different kinds of load Love numbers are involved, one characterizing the vertical displacement and one characterizing the redistribution of mass within the Earth due to the displacement.

4. The vertical displacement of the crust

The vertical displacement of the crust has been computed according to the principles described in Section 3. The integration has been performed numerically; see further Olsson et al (2009). The sea level heights needed for this have been taken from Figure 3; they are thereby represented by discrete values in a grid. The coast-line has been taken from modern maps. The fact that the coast-line moved temporarily during the storm, as low land areas were flooded, has been neglected.

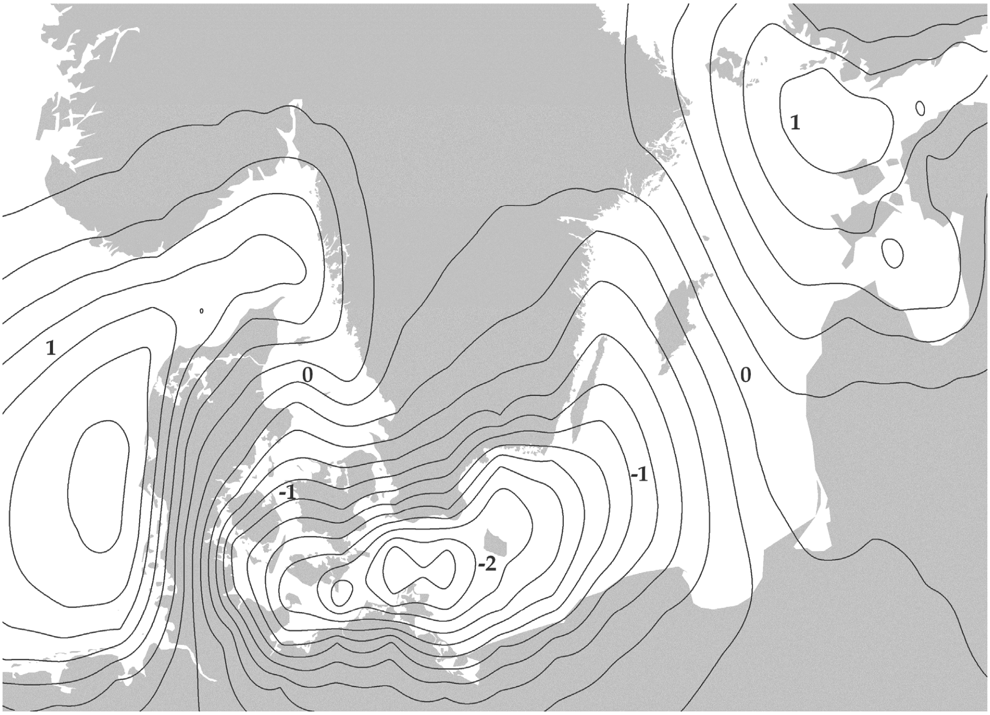

Figure 4. Vertical crustal displacement (cm) caused by the sea level change due to the storm of 1872.

The result of the computations is shown as a map of the vertical crustal displacement; see Figure 4. As can be seen from the map, the maximum downward displacement amounts to

u = - 2.3 cm

(A somewhat similar maximum value was obtained for storm surges in the North Sea by Fratepietro et al (2006).) The maximum area is located east of Denmark, between southernmost Sweden and northernmost Germany. This is not far from the maximum sea level but still somewhat to the east of it because of the particular distribution of the water load shown in Figure 3.

Local upward displacements in Figure 4 are found in the eastern North Sea and the north-eastern Baltic proper. They are caused by the lowered sea level there, cf. Figure 3. The maximum upward displacement is

u = 1.5 cm

located west of Denmark. Thus the maximum difference in vertical displacement amounts to nearly 4 cm.

An interesting feature in Figure 4 is the large gradient of the vertical displacement across Denmark. This corresponds to an east-west tilt of the crust. The maximum tilt or gradient there amounts to

$$\text{grad}\, u = 0.2 \text{ mm/km}$$

or 2 cm in 100 km.

5. The change in gravity

The change in gravity has been computed for one single station, illustrating the extreme effect. The dominating contribution to the gravity change comes from the direct attraction of the additional water mass itself. The other contributions come from the vertical displacement of the crust and the redistribution of mass within the Earth due to the displacement. For a detailed study of this see Olsson et al (2009).

The point chosen for the gravity computations is in south-eastern Denmark, at the end of a long pier in the harbour of Gedser. There is no other land within 100 m from this point. Since the whole effect from the direct attraction, at a point situated 1 m above sea level, comes from water masses within 100 m (Olsson et al, 2009), this station well represents the extreme effect.

The resultant gravity change at the above station, where sea level was 2.6 m above normal, amounts to

$$\Delta g = 108 \text{ µgal}$$

Of this, 104 µgal refers to the direct attraction, 6 µgal to the vertical displacement, and – 2 µgal to the mass redistribution.

6. Triggering of an earthquake?

Colding (1881) reports that an earthquake is said to have been felt on the island of Bornholm in connection with the storm flood. He also states that a fairly common view among people was that this earthquake might be partly responsible for the extreme rise of sea level. This view is of course not realistic, but one could put the question the other way around: Might the extreme rise of sea level be partly responsible for the earthquake?

There are two circumstances of interest here. The first one is the geographical distribution of the vertical displacement of the crust shown in Figure 4, due to the water load. The area of the maximum vertical displacement of the crust is located to the west of Bornholm. This area should also be the area of maximum curvature of the crust, and thereby also of maximum crustal stress caused by the water load.

The other circumstance of interest is the location of the co-called Tornquist zone. This is a deformation zone in the crust, a probable remnant of an old plate boundary. It runs from north-west to south-east through southernmost Sweden and the southern Baltic Sea; it passes just to the west of Bornholm.

Combining these two circumstances we may suggest a possibility: An earthquake going to occur at the Tornquist zone west of Bornholm was triggered by the additional water load on the crust, caused by the storm.

7. Conclusions

The great storm flood of 1872 caused a considerable loading on the crust. It resulted in a maximum vertical downward displacement of the crust of 2.3 cm, in the south-western Baltic, and a maximum upward displacement of 1.5 cm, in the eastern North Sea, making a difference of nearly 4 cm. The maximum tilt of the crust due to the water load was found to be 2 cm per 100 km, across southern Denmark. The extreme gravity change, at Gedser in south-eastern Denmark, was found to be 108 µgal, most of it due to the direct attraction of the additional water.

In addition, the storm flood might possibly have triggered an earthquake west of Bornholm.

References

Baensch, O (1875): Die Sturmfluth vom 12./13. November 1872 an den Ostseeküsten des Preussischen Staates. Zeitschrift für Bauwesen, 25, 156-220.

Colding, A (1881): Nogle Undersøgelser over Stormen over Nord- og Mellem-Europa af 12te-14de November 1872 og over den derved fremkaldte Vandflod i Østersøen. Kongel. Danske Videnskabernes Selskabs Skrifter, Naturvidenskabelig og mathematisk Afdeling, 6/1, 243-304.

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

Farrell, W E (1972): Deformation of the Earth by surface loads. Reviews of Geophysics and Space Physics, 10, 761-797.

Fratepietro, F, Baker, T F, Williams, S D P, Van Camp, M (2006): Ocean loading deformations caused by storm surges on the northwest European shelf. Geophysical Research Letters, 33.

Olsson, P-A, Scherneck, H-G, Ågren, J (2009): Effects on gravity from non-tidal sea level variations in the Baltic Sea. Journal of Geodynamics, 48, 151-156.

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