Nordic Hydrology 4, 1973, 41–53
Published by Munksgaard, Copenhagen, Denmark

SEA LEVEL VARIATIONS IN THE GULF OF BOTHNIA

EUGENIE LISITZIN

Helsinki, Finland

An attempt is made to compute the sea level variations in the Gulf of Bothnia, which is isolated by islands and thresholds from the Baltic Sea proper.
Observations from tide gauges during the 30-year period 1931–1960 were used.
The effect of land uplift was taken into consideration.
The maximum annual deviation in water volume from the long-term mean corresponded to 20.74 km^3.

The principal purpose of this paper is to give a tentative picture of sea level variations in the Gulf of Bothnia in accordance with Recommendation I-4 of the first meeting of experts on the water balance of the Baltic Sea held in Gdynia in 1971. The Gulf of Bothnia forms a sea basin with characteristics deviating in many respects from the general features of the Baltic proper and the Gulf of Finland. While the latter gulf may be considered an immediate continuation of the Baltic basin, the Gulf of Bothnia is more isolated from this basin by islands and thresholds, although the transition area around the Aaland Islands is too wide to allow this gulf to be treated as a practically enclosed region. The following investigation is therefore mainly an attempt to compute the sea level variations in the Gulf of Bothnia and not a study of the causes which are responsible for these variations.

The results of this paper are based principally on the records for the 30-year period 1931–1960. Among the factors influencing sea level data, only the effect of land uplift has been considered in the following study. As is well-known, this effect is more pronounced in the Gulf of Bothnia than in the other parts of the Baltic area.

During the research period 13 gauges have been in operation within the area of the Gulf of Bothnia. The number of tide gauges along the Finnish coast was nine and along the Swedish coast four. From the records the annual mean sea levels for each year in reference to a zero level or a local benchmark are obtained for each tide gauge, and the mean sea level for each of the three decades is computed for each tide gauge, as well as the mean sea level for the entire period 1931–1960.

Then the deviations of each year from the decade means are computed for each tide gauge, as well as the deviations from the 1931–1960 mean.

Corrections are then applied for the land uplift, and the resulting data give a conception of the variability of the annual sea level changes in different decades. The values for the secular changes for the Finnish stations are based on the results achieved by Lisitzin (1964); those for the Swedish stations are based on results given by Rossiter (1967). In this connection it may be pointed out that the period which Lisitzin used in her research on land uplift along the Finnish coast (1924–1960) coincides rather closely with the period on which the results of this paper are based. These data on land uplift also are in keeping with the results achieved by geodetic precise levelling (Kääriäinen 1966). The rates of land uplift given by Rossiter are based on longer periods. However, they also cover the 30 years 1931–1960, and are therefore, undoubtedly preferable to the results given, for instance, by Bergsten (1930). Of course, the methods used by Rossiter, on the one hand, and the author, on the other hand, are considerably different. A comparison of the rates of the computed land uplift shows, however, that the period on which the computations are based is, as a rule, more significant than the method used.

Studying the annual mean sea level data for the Finnish stations more closely, one could gather that the results of three of the stations, namely Oulu, Vaasa and Turku, deviated more frequently than the other stations from the continuous course of the changes in sea level when progressing along the coast. This result is by no means surprising, since these stations are situated in the inner parts of the skerries and are thus more subject to the local effects than the rest of the stations. Therefore, these three stations have not been taken into consideration in this paper. Thus there remained five stations in the Bothnian Bay and the same number of stations in the Bothnian Sea. However, the area of the Bothnian Bay is approximately half the area of the Bothnian Sea including the Archipelago and the Aaland Sea. This fact forces us to reduce the number of stations in the Bothnian Bay. As the records for Furuögrund were not quite satisfactory, it seemed appropriate to disregard them. Among the

Finnish stations the choice was between Raahe and Pietarsaari. It seemed more adequate to include Pietarsaari in the research, as Raahe is more influenced by the piling-up effect of the wind and this effect could therefore be too highly accentuated in the final results, since Kemi, too, was included in the study. There remained eight stations: five of them were Finnish and three Swedish. If we take into account that the station Kemi does not represent as much the eastern coast of the Gulf of Bothnia as the innermost parts of it, while Degerby is, in fact, a representative of the approaches to the basin, the selection of the eight stations seems to be the best possible. The average annual values for these eight stations are given in Table 1 as well as the mean sea level for the whole Gulf of Bothnia corresponding to the three decades. Moreover, in the last column of the Table we find the mean sea level of the entire Gulf determined for the 30-year period, 1931–1960. In order to get a comparison with the results based on a greater number of stations, the corresponding data for 13, 10 and 8 stations have been given in Table 2.

The values for the separate stations in Table 1 give an idea of the variability of the data in time and space reflecting, in addition, the characteristics of the slope of the water surface during the years in question.

As could be expected, the variability was most pronounced in the inner parts of the Gulf of Bothnia, and least marked in the South. It may, for instance, be mentioned that the amplitude of the annual mean values amounts to 29.4 cm for Kemi and to 23.0 cm for Degerby. For the Gulf of Bothnia, as a whole, the amplitude is 25.4 cm. Kemi and Degerby are also exceptional in so far as the maximum and minimum sea levels occur at these stations more frequently than at the other stations. During the 30-year period the annual mean sea level was at its highest at Kemi in nine years, and at its lowest in ten years. For Degerby the corresponding values are five and six. This implies that at the two stations the extreme values were recorded in no less than 50 per cent of all cases. Thus the most frequently recorded direction of the slope of the water surface coincides with the main axis of the sea basin. The height difference amounts to 5.0–5.5 cm in the most pronounced cases. It could also be established that in 27 of the 30 years sea level heights differed between the Swedish and the Finnish coasts, both represented by three stations. In this case the maximum height difference is, however, only 2 cm. The mean sea level on the east coast seems somewhat more frequently to be higher than than lower than the sea level on the west coast.

Before we proced to the discussions of the annual cycle in sea level in the Gulf of Bothnia, attention must be paid to the question as to which of the sea level stations used above may be considered the best representative of the Gulf of Bothnia as a whole. The selection of such a station may be of im-

Table 1.

The annual mean sea level (cm) in the Gulf of Bothnia during different years and decades.

	Kemi	Pietarsaari	Kaskinen	Mänty-luoto	Degerby	Björn	Drag-hällan	Ratan	Gulf of Bothnia	
									10 years	30 years
1931	– 0.9	– 0.7	– 0.2	– 0.4	0.7	– 0.2	– 0.5	1.4	– 0.1	– 0.8
1932	7.4	7.0	6.8	6.8	6.4	5.6	5.7	7.5	6.7	6.0
1933	– 7.0	– 6.6	– 6.3	– 5.9	– 4.8	– 5.6	– 6.9	– 7.0	– 6.3	– 7.0
1934	4.6	4.7	4.0	3.7	2.9	3.1	3.8	5.5	4.0	3.3
1935	4.8	5.1	5.4	5.3	5.2	5.9	6.4	5.6	5.5	4.8
1936	– 2.3	– 2.4	– 2.5	– 2.2	– 1.7	– 1.4	– 1.5	– 2.9	– 2.1	– 2.8
1937	– 9.9	– 9.3	– 8.3	– 8.1	– 7.2	– 6.1	– 6.5	– 9.3	– 8.1	– 8.8
1938	14.7	13.0	12.5	11.7	10.4	10.6	11.7	13.0	12.2	11.5
1939	– 9.4	– 8.5	– 8.4	– 8.3	– 8.7	– 8.4	– 8.8	– 9.1	– 8.7	– 9.4
1940	– 2.4	– 2.2	– 2.9	– 3.0	– 2.9	– 3.5	– 3.6	– 4.9	– 3.2	– 3.9

1941	–17.2	–16.6	–15.4	–15.1	–14.0	–13.8	–14.3	–15.2	–15.2	–13.5
1942	– 5.3	– 5.2	– 5.0	– 5.3	– 5.1	– 5.2	– 6.4	– 5.5	– 5.4	– 3.7
1943	12.2	11.2	10.5	9.8	8.7	8.0	9.7	11.2	10.2	11.9
1944	5.4	3.8	3.7	3.1	3.0	4.1	3.9	5.1	4.0	5.7
1945	– 2.5	0.0	0.8	1.6	3.0	3.8	1.9	0.9	1.2	2.9
1946	0.0	– 0.3	– 0.3	– 0.7	– 1.2	– 0.8	– 0.4	– 0.7	– 0.5	1.2
1947	–13.8	–13.8	–13.4	–13.0	–12.6	–14.5	–14.0	–14.1	–13.7	–12.0
1948	7.6	6.3	5.8	6.0	5.7	5.2	4.6	5.0	5.8	7.5
1949	11.6	10.0	9.4	9.5	9.0	8.7	9.3	10.2	9.7	11.4
1950	2.4	4.1	4.2	3.7	3.9	4.8	5.3	2.7	3.9	5.6
1951	– 2.4	– 2.9	– 5.3	– 6.2	– 7.5	– 7.2	– 7.8	– 5.2	– 5.6	– 6.6
1952	6.3	6.2	5.6	5.7	6.0	6.2	6.0	6.5	6.1	5.1
1953	8.4	8.3	5.4	4.7	3.1	4.5	4.7	6.6	5.7	4.7
1954	2.3	0.9	1.7	0.4	– 0.8	– 0.2	1.0	0.0	0.7	– 0.3
1955	2.2	3.1	3.9	4.1	4.5	3.9	2.7	2.8	3.4	2.4
1956	– 0.3	1.0	2.1	2.6	3.7	2.6	3.0	1.3	1.8	0.8
1957	5.0	4.6	5.5	6.2	5.8	5.4	5.1	5.7	5.4	4.4
1958	– 2.1	– 2.6	– 1.5	– 0.9	– 0.1	– 1.4	– 1.8	– 1.6	– 1.5	– 2.5
1959	– 5.2	– 6.0	– 6.2	– 5.9	– 5.3	– 5.4	– 5.6	– 4.8	– 5.5	– 6.5
1960	–13.7	–12.2	–10.9	–10.6	– 9.4	– 8.6	– 8.0	–11.0	–10.6	–11.6

Table 2.
The annual mean sea level (cm) of the Gulf of Bothnia computed on the basis of 13, 10 and 8 stations.

	13 stations	10 stations	8 stations
1931	– 0.2	– 0.1	– 0.1
1932	7.2	6.8	6.7
1933	– 6.2	– 6.2	– 6.3
1934	4.4	4.4	4.0
1935	5.5	5.7	5.5
1936	– 2.0	– 2.0	– 2.1
1937	– 8.7	– 8.6	– 8.1
1938	12.3	12.2	12.2
1939	– 8.9	– 8.9	– 8.7
1940	– 3.3	– 3.4	– 3.2
1941	–15.4	–15.4	–15.2
1942	– 5.2	– 5.3	– 5.4
1943	10.6	10.4	10.2
1944	4.0	4.0	4.0
1945	0.7	0.8	1.2
1946	– 0.5	– 0.5	– 0.5
1947	–13.5	–13.7	–13.7
1948	6.0	6.0	5.8
1949	9.8	9.9	9.7
1950	3.6	3.9	3.9
1951	– 5.3	– 5.2	– 5.6
1952	5.8	5.9	6.1
1953	6.0	6.0	5.7
1954	0.9	0.9	0.7
1955	3.5	3.3	3.4
1956	1.8	1.8	1.8
1957	5.5	5.5	5.5
1958	– 1.6	– 1.7	– 1.7
1959	– 5.5	– 5.5	– 5.5
1960	–11.1	–10.9	–10.6

portance, if it is necessary to obtain a rapid answer concerning the sea level and the water volume variations in the entire Gulf of Bothnia. A comparison of the values for the particular stations with the results for the Gulf as a whole has shown that in this respect the station of Kaskinen gives the most satisfactory result. The probable mean deviation between the two series is 0.23

cm; the largest single deviation is 1.0 cm. These values correspond approximately to one, respectively, four per cent of the amplitude of the variation and they are thus not pronounced. Thus Kaskinen may well be substituted for the whole Gulf of Bothnia, for instance, in all the cases where the current water balance is studied.

The problem of the annual cycle of sea level in the Gulf of Bothnia is also an interesting question which may be significant in many respects. Table 3 gives the monthly means for the particular stations and the corresponding values for the whole Gulf. All the data were reduced to the average sea level for the period 1931–1960. The results for the separate stations show quite distincly the annual changes of the slope of the water surface during different months. This phenomenon has been studied earlier in more detail (Lisitzin 1957) If we compare the data for the Swedish coast with those for the Finnish coast, we note that the deviations from the smooth and continuous course are more numerous in the former case than in the latter case. However, these deviations are, as a rule, not very pronounced. Also concerning the annual cycle the close relationship between tht data for the whole Gulf of Bothnia and those for Kaskinen may be noted. The probable mean deviation amounts to 0.25 cm, the largest deviation is 0.9 cm. Special attention may be paid to the differences in sea level between the east and the west coast of the Gulf of Bothnia. The mean sea level for the three Finnish stations, Pietarsaari, Kaskinen and Mäntyluoto, on the one hand, and for the three Swedish stations, on the other hand, are given in Table 4. In the last line of this Table we find the differences between these data. These differences show that the mean sea level along the Finnish coast stands relatively higher than along the Swedish coast in winter, lower in summer. This fact is surely due to the predominant winds with southerly components in wintertime, followed by a more pronounced inflow of water masses, and the effect of Coriolis force on these water masses.

In all the above computations the mean sea level for a definite period has been chosen as the basis for all data. It is, however, a well-known fact that the water surface does, as a rule, not follow the geoid, but deviates from it, in some cases quite considerably. The Baltic Sea and the Gulf of Bothnia are no exceptions in this respect. The author (1957) has shown that the sea level stands some 9.5 cm higher at Kemi than at Degerby, and differences in mean sea level relative to Degerby have been determined for all the tide gauges along the Finnish coast of the Gulf of Bothnia. For the Swedish coast the height differences have been estimated only approximately. Table 5 gives the annual cycle of the mean sea level for the separate station. The Table shows very distinctly that the sea level increases in all months from Degerby towards the inner parts of the Gulf.

Table 3.
The annual cycle in mean sea level (cm) in the Gulf of Bothnia during different decades.

	J	F	M	A	M	J	J	A	S	O	N	D
1931–1940												
Kemi	9.7	– 0.3	–14.0	–13.2	–21.6	– 6.9	3.5	6.8	1.4	10.2	15.2	9.0
Pietarsaari	7.5	1.1	–11.8	–10.5	–19.6	– 5.8	4.3	6.6	3.1	9.2	9.9	5.9
Kaskinen	5.7	0.3	–10.6	– 9.5	–18.4	– 5.5	5.5	7.1	4.0	8.6	8.4	4.7
Mäntyluoto	4.1	0.3	– 9.5	– 8.9	–17.4	– 5.2	5.7	7.2	4.6	8.3	7.2	3.7
Degerby	2.3	0.6	– 9.3	– 8.5	–16.6	– 5.0	6.6	7.8	5.6	8.1	5.8	2.8
Björn	4.0	– 0.1	– 9.8	– 8.6	–17.2	– 5.7	6.3	7.4	5.2	8.5	6.5	3.9
Draghällan	4.9	– 0.5	–11.0	– 9.5	–17.1	– 4.3	6.5	7.5	4.0	8.4	7.2	3.8
Ratan	7.5	– 1.8	–11.5	–10.1	–17.7	– 6.2	4.6	9.2	1.6	8.4	9.3	5.5
Gulf of Bothnia	5.7	0.0	–10.9	– 9.8	–18.2	– 5.6	5..4	7.4	3.7	8.7	8.7	4.9

1941–1950												
Kemi	– 0.8	– 4.5	– 6.7	– 2.2	–13.6	– 6.3	– 3.1	– 0.2	7.6	13.2	2.4	13.0
Pietarsaari	0.1	– 4.5	– 6.3	– 1.7	–13.0	– 4.7	– 1.6	1.0	5.9	12.5	0.2	11.2
Kaskinen	0.6	– 4.7	– 6.3	– 1.3	–12.1	– 3.3	0.3	1.7	5.0	10.5	– 0.1	10.2
Mäntyluoto	0.0	– 5.0	– 6.2	– 1.7	–12.0	– 2.8	1.0	2.2	4.9	10.6	– 0.5	9.0
Degerby	0.0	– 5.0	– 6.2	– 2.8	–11.3	– 1.8	2.7	2.7	4.5	10.3	– 0.8	7.6
Björn	1.2	– 6.6	– 7.3	– 2.8	–11.5	– 2.3	2.3	3.4	3.9	9.8	0.9	9.2
Draghällan	– 0.1	– 5.5	– 7.6	– 1.8	–10.9	– 1.2	2.1	2.8	4.3	8.9	– 0.4	8.9
Ratan	0.4	– 4.8	– 8.7	– 2.6	–12.9	– 3.8	– 0.1	1.6	5.2	11.6	0.3	13.1
Gulf of Bothnia	0.2	– 5.1	– 6.9	– 2.1	–12.2	– 3.3	0.4	1.9	5.2	10.9	0.2	10.3
1951–1960												
Kemi	10.4	– 7.0	–17.7	–14.7	–13.9	– 2.0	3.2	4.7	7.9	8.4	5.1	16.9
Pietarsaari	10.6	– 6.0	–17.6	–14.5	–12.9	– 3.0	3.6	5.6	8.3	7.4	3.2	15.4
Kaskinen	11.4	– 5.7	–18.5	–14.8	–12.7	– 4.3	3.8	6.2	8.6	7.6	2.7	14.9
Mäntyluoto	11.4	– 6.0	–18.1	–14.3	–12.2	– 4.1	4.4	6.3	9.0	7.8	2.0	13.9
Degerby	11.3	– 6.2	–18.6	–14.8	–11.1	– 4.5	5.2	7.2	9.4	8.0	1.6	12.9
Björn	11.6	– 6.1	–19.4	–15.0	–12.3	– 3.4	4.2	6.3	9.0	8.3	2.5	14.1
Draghällan	10.0	– 6.1	–18.0	–13.7	–11.4	– 3.8	4.7	6.9	8.1	6.5	2.1	13.7
Ratan	8.9	– 6.8	–18.4	–13.7	–11.5	– 2.8	4.1	6.1	8.5	7.5	3.3	14.8
Gulf of Bothnia	10.7	– 6.8	–18.3	–14.4	–12.2	– 3.5	4.2	6.2	8.6	7.7	2.8	14.7
1931–1960												
Gulf of Bothnia	5.7	– 3.7	–12.0	– 8.8	–14.2	– 4.1	3.3	5.2	5.8	9.1	3.9	10.0

Table 4.
The annual cycle in mean sea level (cm) for the Finnish coast (Pietarsaari, Kaskinen, Mäntyluoto) and for the Swedish cost (Björn, Draghällan, Ratan) during different decades.

	J	F	M	A	M	J	J	A	S	O	N	D
1931–1940												
Finnish coast	' 5.8	0.6	–10.6	– 9.6	–18.5	– 5.5	5.2	7.0	3.9	8.7	8.5	4.8
Swedish coast	5.5	– 0.8	–10.8	– 9.4	–17.3	– 5.4	5.8	8.0	3.6	8.4	7.7	4.5
Difference	0.3	1.4	0.2	– 0.2	– 1.2	– 0.1	– 0.6	– 1.0	0.3	0.3	0.8	0.3
1941–1950												
Finnish coast	0.2	– 4.7	– 6.3	– 1.6	–12.4	– 3.6	– 0.1	1.6	5.3	11.2	– 0.1	10.1
Swedish coast	0.5	– 5.6	– 7.9	– 2.4	–11.8	– 2.4	1.4	2.6	4.5	10.1	0.3	10.4
Difference	– 0.3	0.9	1.6	0.8	– 0.6	– 1.2	– 1.5	– 1.0	0.8	1.1	– 0.4	– 0.3
1951–1960												
Finnish coast	11.1	– 5.9	–18.1	–14.5	–12.5	– 3.8	3.9	6.0	8.6	7.6	2.6	14.7
Swedish coast	10.2	– 6.3	–18.6	–14.1	–11.7	– 3.3	4.3	6.4	8.5	7.4	2.6	14.2
Difference	0.9	0.4	0.5	– 0.4	– 0.8	– 0.5	– 0.4	– 0.4	0.1	0.2	0.0	0.5
1931–1960												
Difference	0.3	0.9	0.8	0.1	– 0.9	– 0.6	– 0.8	– 0.8	0.4	0.5	0.1	0.2

Table 5.
The annual cycle of sea level (cm) in the Gulf of Bothnia showing the slope of the water surface (1931–1960).

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Kemi	15.9	5.5	− 3.1	− 0.6	− 6.9	4.5	10.7	13.2	15.1	20.1	17.0	22.4	9.5
Pietarsaari	12.5	3.3	− 5.5	− 2.5	− 8.8	1.9	8.5	10.5	12..2	16.1	10.8	17.2	6.4
Kaskinen	8.0	− 1.3	− 9.7	− 6.4	−12.1	− 2.3	5.3	7.1	8.0	11.0	5.8	12.0	2.1
Mäntyluoto	6.5	− 2.2	− 9.9	− 7.0	−12.5	− 2.7	5.0	6.6	7.5	10.2	4.2	10.2	1.3
Degerby	4.6	− 3.5	−11.3	− 8.7	−13.0	− 3.4	4.9	5.9	6.5	8.8	2.2	7.8	0.0
Björn	6.3	− 3.6	−11.5	− 8.1	−13.0	− 3.1	4.9	6.6	6.7	9.5	4.0	9.7	0.7
Draghällan	6.5	− 2.4	−10.6	− 6.7	−11.5	− 1.5	6.0	7.3	7.1	9.5	4.6	10.4	1.6
Ratan	10.6	0.5	− 7.9	− 3.8	− 9.1	0.7	7.8	10.6	10.1	14.2	9.3	16.1	5.0

For the problem of the water balance of the Gulf of Bothnia, not so much the variations of the sea level as the changes in water volume are of interest. Using the data given by Witting (1918) for the area of the Gulf of Bothnia, which, including the Archipelago and the Aaland Sea, amounts to 117.100 km^2, we get the following values. The maximum annual deviations in the water volume in the Gulf of Bothnia were, during the various periods:

1931–1940	24.74 km^3,
1941–1950	29.74 km^3,
1951–1960	19.56 km^3,
1931–1960	29.74 km^3.

The greatest positive deviation in water volume occurred in 1943, amounting to 13.93 km^3, the largest negative deviation in 1941, when it was –15.81 km^3.

The water volume deviations in the separate decades, relative to the 30-year period, are

1931–1940	–0.82 km^3,
1941–1950	1.99 km^3,
1951–1960	–1.17 km^3.

Owing to the character of the Gulf of Bothnia the determination of the monthly mean sea levels is of secondary significance. However, it may be of interest to mention in this connection the extreme values of monthly mean sea level during the 30-year period. In January 1932 the sea level was 37.8 cm, corresponding to 44.26 km^3, in February 1947 –50.7 cm, which resulted in a water volume of –59.37 km^3. The amplitude is thus 103.63 km^3, or almost 4 times larger than the amplitude of the deviations during different years.

It will be interesting to compare these data with the results for the whole Baltic basin.

REFERENCES

Bergsten, F. (1930) The changes of land-level at the Swedish coasts computed with regard to periodic fluctuations of sea level. *3e Conf. Hydrol. États Baltique 26,* 1–6.

Kääriäinen, Erkki (1966) The Second Levelling of Finland in 1935–1955. *Veröff. Finn. Geod. Inst.,* paper no. 61.

Lisitzin, Eugenie (1957) The annual variation of the slope of the water surface in the Gulf of Bothnia. *Comment. Phys.-Math. 20,* 1–20.

Lisitzin, Eugenie (1964) Contribution to the knowledge of land uplift along the Finnish coast. *Fennia 89,* 1–22.

Rossiter, J. R. (1967) An analysis of annual sea level variations in European waters.

Geophys. J. R. astr. Soc. 12, 259–299.
Witting, Rolf (1918) Hafsytan, geoidytan och landhöjningen utmed Baltiska Hafvet och vid Nordsjön. *Fennia 39,* 1–347.

Received 10 October 1972.

Address:
Skarpskyttegatan 1 C 27,
Helsinki,
Finland.