DETERMINATION OF MEAN SEA LEVEL IN THE NORTHERN PART OF THE BALTIC

Summary of the present results

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The problem of the determination of mean sea level has old traditions in the Baltic. In some parts of the Gulf of Bothnia, land upheaval is so pronounced that it may easily be observed during a lifetime. It is therefore by no means surprising that there was already available, before the start of the first regular sea level observations along the Finnish coast in the middle of the nineteenth century, occasional information on sea level, the earliest of them dating from the year 1697.

However, although creating a considerable interest concerning the question of the changes in mean sea level, the vertical movements of the earth's crust in Northern Europe render the problem more complicated than in other regions. For the determination of mean sea level along the coasts of the Baltic, it is not sufficient to compute and eliminate the effect of tides and the permanent or occasional influence of meteorological factors. Land uplift must also be taken into consideration. It must, moreover, be kept in mind that the continuous decrease in mean sea level, such as it appears in the tide records, represents since the beginning of this century the effect of the vertical movement of the coast reduced by the general increase in the total volume of water in the oceans and seas caused by the melting of continental ice.

In the Baltic, the determination of the mean sea level must thus be divided into three main sections (1, 2 and 3) and three additional subsections (*a*, *b* and *c*) :

(1) Elimination of the effect of :
    (a) astronomical,
    (b) meteorological and
    (c) hydrographic factors;
(2) Estimation of the influence of land uplift, also called the secular variation;
(3) Consideration of the increase of the total volume of water in the oceans.

The effect of the semi-diurnal and diurnal tides need not be discussed in more detail in this connection, as its elimination does not present any great difficulties. Moreover, at least in comparison with other disturbances, the amplitudes of these tides are quite slight in the Baltic. Passing on to the nodal tide, over a period of 18.6 years, it may be mentioned that according to the results of ROSSITER [7] the amplitude of this tide varies along the Finnish coast between 3.4 and 11.2 mm, being on an average 5.9 mm. The significance of this tide is thus not very marked, but is by no means negligible.

The elimination of the effect of the meteorological factors is probably the most difficult part of the task in determining the mean sea level. The Baltic and especially its two large gulfs bordering on Finland are shallow. The sea level reacts, therefore, very strongly to the influence of meteorological changes. The cycle of these changes is partly annual, but occasional fluctuations are more pronounced and may frequently cause considerable distortion of the average conditions. The significance of the method for the elimination of the meteorological effect is seen distinctly in the fact that different authors obtained varying values for land upheaval along the Finnish coast using for its determination different methods of elimination. It may be appropriate to give in this connection a short account, at least, of the more important and interesting of these methods.

One of the first extensive attempts to determine land uplift along the Finnish coast was made by WITTING [8]. Referring to the combined influence of air pressure and wind, he introduced the term *anemo-baric* effect and computed, using air pressure data, the magnitude of this effect not only for the Baltic, but also for the transition area around Denmark and the North Sea. WITTING also took into consideration the water discharge by rivers, precipitation, evaporation and density of the water. His first paper was based on the tide pole observations made during the years 1898 to 1912, but he later continued these observations over a period of 30 years from 1898 to 1927 [9].

Ten years after the appearance of WITTING's second paper, a study on the same problem was published by HELA [1]. The method used by HELA for the elimination of the meteorological effect is based on the presumption that these factors mainly affect the sea level in two different ways :

(a) by non-secular changes of the total water amount in the Baltic, which, of course, is the same at all stations, and

(b) by the variations in the mean slope of the water surface which is supposed to be a plane.

In this study the sea level data themselves could therefore serve for the process of elimination of the effect of meteorological disturbances. The period used by HELA covers the 30 years from 1922 to 1951.

In a recent paper ROSSITER [7] made a new approach to the problem, trying once more to eliminate the influence of the meteorological contribution to sea level with the aid of a method based on air pressure data. For the stations in the Baltic and its large gulfs, the contribution from local winds and air pressure was represented by data from Haparanda, Warsaw and Bergen. These places form a triangle covering the Baltic and its coastal region. As sea level in the named basin is greatly affected by the meteorological conditions in the North Sea, air pressure data from the Bergen, De Bild and Stornoway triangle were used, in addition. In order to be able to determine the effect of the nodal tide upon the sea level, ROSSITER chose for his study the 19 year period 1940-1958.

The principal purpose of the papers mentioned above was not the determination of the meteorological effect itself, but its elimination from the sea level data in order to compute the secular variations. The author [3, 4] chose another way to tackle the problem by studying the annual cycle of the meteorological and hydrographic effect upon sea level fluctuations. It is well-known that the average water surface rises slightly towards the inner parts of the Gulf of Bothnia and the Gulf of Finland. This slope is caused by three factors, all having a similar influence :

(*a*) the influence of the general air pressure distribution which, on an average, shows lower values in the north than in the south;

(*b*) the piling-up effect of the wind;

(*c*) the contribution of decreasing density of sea water. The determination of the effect of these factors, even for average conditions, is not always easy. However, the good conformity between the annual course of the deviations in sea level between the innermost part of the Gulf of Bothnia and its approaches, on the one hand, and the computed monthly effect of the three factors contributing to these deviations, on the other hand, justifies the method. It may be mentioned that the difference in water height between Kemi (situated in the inner part of the Gulf of Bothnia) and Degerby (lying in the southern part of the Aland Islands) is, on an average, 9.5 cm, the air pressure effect being 1.8 cm, the wind effect 3.0 cm, and the density effect 4.7 cm. In order to give a conception of the annual fluctuations of the total height differences and the partial effects of the three contributing terms, the relevant data for the different seasons are given in table 1. This table shows that there appear, in the course of the year, pronounced anomalies in the effect of air pressure and wind. However, these correspond quite well with observed water height differences. The values concerned are in this case :

January	April	July	October
13.1 cm	7.5 cm	5.4 cm	11.2 cm

In fact, it is only in January that the deviation between the two sets of data is noteworthy, in July it is only 7 %, in the remaining months less than 2 or even 1 %.

In the Gulf of Finland the average increase in sea level from the area around Degerby to the region of the boundary between Finland and the U.S.S.R. is 5.0 cm, the proportionate influence of air pressure, wind and density effect being respectively 0.0, 1.3 and 3.7 cm.

The above data show the considerable contribution of density to the total slope. This contribution is, compared with the other effects, largest during the warm season. In the Baltic, characterized by a marked decrease of salinity from the outer parts of the basin towards its inner parts, the density changes are mainly due to this factor. The significance of the variation of water temperature is fairly slight. This fact is distinctly reflected in the limited seasonal fluctuations of the density effect in table 1.

TABLE 1

The meteorological and hydrographic effect on the water height differences in the Gulf of Bothnia during different seasons

	Air pressure effect	Wind effect	Density effect	Total effect
January	2.0 cm	8.8 cm	5.2 cm	16.0 cm
April	1.8 cm	0.9 cm	4.9 cm	7.6 cm
July	0.3 cm	1.0 cm	4.5 cm	5.8 cm
October	2.8 cm	4.0 cm	4.5 cm	11.3 cm

A height difference of, say, 9.5 cm seems not to be significant when considering great heights or great depths. There are, however, numerous cases where an accuracy of a fractional part of this value is required. In this connection it may suffice to refer to precise levelling.

As mentioned above, WITTING, HELA and ROSSITER computed the vertical movement of the earth's crust along the Finnish coast. These data are reproduced in table 2 which contains, moreover, the corresponding data computed by MODEL [6] and the author [5] by less extensive and accurate methods. In addition, values on land uplift published by KÄÄRIÄINEN [2] on the basis of precise levelling are included in the table.

Before passing on to discuss the results given in table 2, it must be pointed out that all data based on sea level observations (the first six columns) do not give the land uplift as such, but are somewhat reduced by the effect of the general increase in the volume of the water in the oceans and seas. The exact value of this increase is, however, not known. Different authors give different estimates. These vary between 0.5 and 1.1 cm per 10 years. The probable reduction is thus somewhat less than 1.0 cm per 10 years and all the relevant data must be augmented by this amount in order to make them comparable with the results of precise levelling.

WITTING drew, with the aid of his data, maps which located the

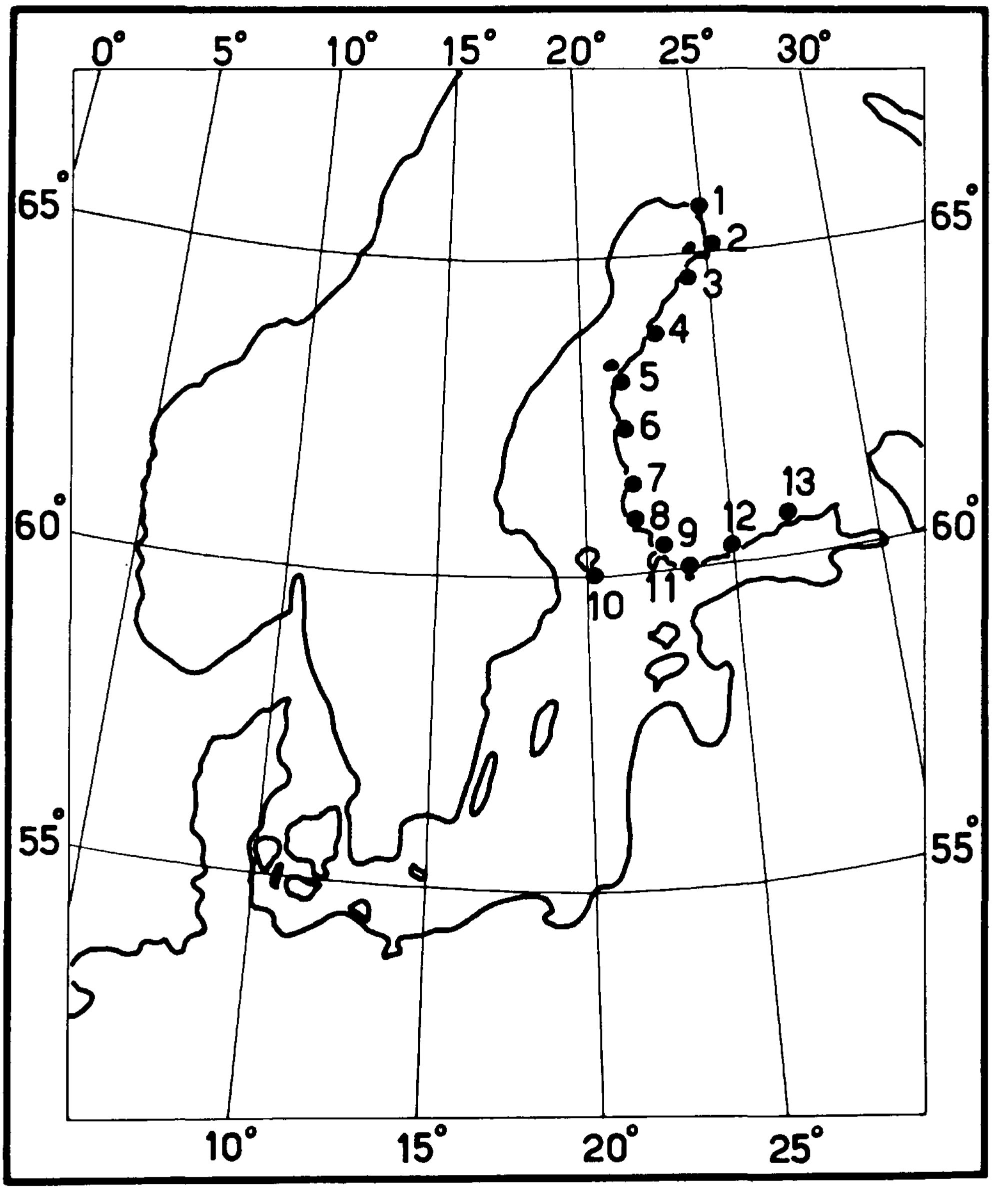
TABLE 2

Land uplift (cm per 10 years) along the Finnish coast according to different authors

	WITTING 1898-1912	WITTING 1898-1927	MODEL 1904-1937	HELA 1922-1951	LISITZIN 1926-1955	ROSSITER 1940-1958	KÄÄRIÄINEN Precise levelling
1. Kemi	—	—	7.2*	6.4	6.6	8.5	8.5
2. Oulu/Uleåberg	10.3	10.7	6.3	6.3	6.8	7.0	8.2
3. Raahe/Brahestad	—	—	7.5*	7.4	8.1	8.0	9.0
4. Pietarsaari/Jakobstad .	—	—	8.7	7.6	9.5	9.2	8.8
5. Vaasa/Vasa	9.2	8.7	8.0*	7.2	8.3	7.6	8.8
6. Kaskinen/Kasko	—	—	6.8*	7.6	7.5	6.7	7.7
7. Mäntyluoto	7.4	6.6	6.8	6.5	7.3	5.3	7.0
8. Rauma/Raumo	—	—	—	5.9	—	3.9	6.8
9. Turku/Åbo	—	—	3.3*	4.8	5.4	2.5	5.3
10. Degerby	—	—	3.3*	5.1	—	—	—
11. Hanko/Hangö	4.5	4.0	3.6	3.5	—	1.1	3.6
12. Helsinki/Helsingfors ..	0.8	2.8	2.8	3.1	—	—0.4	2.9
13. Hamina/Fredrikshamn .	—	—	3.6	2.2	—	—0.4	2.7

region of the most marked land uplift within the Baltic to the northernmost part of the Swedish coast bordering the Gulf of Bothnia. Table 2 shows that, according to all remaining papers, there appears to be a distinct maximum in the region around Raahe and Pietarsaari. The data of MODEL, HELA and the author, which to a large extent are based upon the same records, do not vary much one from the other, their general trend being similar. Least satisfactory are the results for Turku. ROSSITER's data indicate a somewhat more marked land uplift in the north (Kemi and Oulu) than the corresponding values given by other authors (except WITTING), while in the south and east (from Mäntyluoto to Hamina) the picture is the reverse. According to ROSSITER, land sinking should occur at Helsinki and Hamina. The results being based on different periods, it is, of course, not excluded that the deviations are the consequence of rapid fluctuations in the process of land upheaval. However, it can hardly be expected that such considerable anomalies as appear in table 2 are caused by real changes in the character of the phenomenon. It seems to be more probable that they are due to the different methods used for the elimination of the meteorological effect. This problem must therefore for the time being be considered as the most crucial factor in the efforts to determine the mean sea level along the Finnish coast.

(*) MODEL classified this station as *less good.*



Position of the tide gauges along the Finnish coast.
The numbers refer to the stations enumerated in table 2.

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