THE INFLUENCE OF WATER DENSITY VARIATIONS ON SEA LEVEL IN THE NORTHERN BALTIC

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PATTULLO, MUNK, REVELLE and STRONG [6] (*) have shown in a thorough investigation of the seasonal oscillation of sea level that there is a considerable analogy between the monthly means of tidal records and the corresponding data determined by using the annual variations in water density. This correspondence is marked, however, in warm and temperate zones only; in the higher latitudes the relationship is indefinite.

Annual variations in the level of the Baltic differ in certain respects from the pattern characterizing adjacent regions. On ocean coasts located in the same latitudes as the Baltic, the fairly marked maximum of the monthly mean level generally occurs in November or December [4]. In the Baltic, however, we get a relatively prolonged maximum, interrupted by a secondary minimum in November, covering the entire period from August to December. The longest series of tidal records on the coasts of Finland is that of Hangö/Hanko (52° 49′ N, 22° 58′ E) and covers the years 1888-1957. The monthly means of these records, listed herewith, are very instructive for our purposes :

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
4.2	—1.4	—10.9	—11.5	—13.4	—4.6	4.2	7.8	7.8	6.6	3.7	7.5 cm

Although the discrepancy between the Baltic and adjacent seas is probably, at least to some extent, the result of the effect produced by the semi-annual constituent Ssa [3], it may be of interest to examine the possible influence of fluctuations in water density over total variations in the level of this sea. GRANQVIST's [1] investigations of the temperature and salinity in the northern part of the Baltic form a valuable basis for elucidating this question. GRANQVIST, through the use of harmonic constants reduced the means of observations carried out from 1921 to 1930 at hydrographic stations located on outlying islands. Data on temperature and salinity are thus available, for every ten metres of depth between the surface and bottom, on the first, eleventh and twenty-first days each month. This enables calculation of the specific volume on the corresponding days, and hence evaluation of sea level variations resulting therefrom.

In two previous investigations regarding the determination of sea level differences in the gulf of Bothnia and the gulf of Finland [2, 5], a depth of 20 metres was selected as a datum level for calculating the slope due to unequal water density in different sections of the gulfs. Notwith-

(*) The numbers between brackets refer to the bibliography.

standing the large number of possible objections to such a procedure, the method is justified by the satisfactory results. In this connection due allowance must be made for the fact that the tide gauges whose records are compared with calculations based on varying water density are all located on the coast where depths never exceed 20 metres. It follows that this same depth may also be used as a datum in the present research.

Table 1 shows sea level variations due to density fluctuations for eight hydrographic stations in the gulfs of Bothnia and Finland, or in the northern part of the Baltic properly so called, for the first day of each month. The stations concerned and their geographic coordinates are the following :

Ulkokalla	64° 20′ N, 23° 27′ E
Isokari/Enskär	60° 43′ N, 21° 01′ E
Märket	60° 18′ N, 19° 08′ E
Jungfruskär	60° 08′ N, 21° 04′ E
Utö	59° 47′ N, 21° 22′ E
Russarö	59° 46′ N, 22° 57′ E
Tammio/Stamö	60° 24′ N, 27° 26′ E
Seivästö/Styrsudd	60° 11′ N, 29° 02′ E

The depth of water at the points of observation at stations Ulkokalla, Isokari, Tammio and Seivästö is slightly more than 20 metres, whereas at Russarö it is approximately 30 metres, at Jungfruskär 40 metres, at Utö 90 metres, and at Märket 100 metres.

An examination of Table 1 will immediately show that differences between the various stations are not very marked. This result is manifestly derived from the fact that the variations are primarily caused by seasonal fluctuations in temperature. Thus the maximum at Ulkokalla is less marked than at other stations, since the water at this station, which is northernmost in the series, becomes less warm than in the other regions examined. The decrease in the maximums as one progresses southwards in the gulf of Finland is however due to the effect of salinity. According to GRANQVIST's investigations, it may on the average be assumed that the warming of water in the spring and summer is accompanied by a decrease in salinity in the upper layers of the Baltic and by an increase in the lower layers. The level separating the two layers varies to some extent, but is usually located at a depth of 20 to 40 metres. The eastern sections of the gulf of Finland are an exception to this rule, the level of separation at Tammio already being at a depth varying from 15 to 8 metres. At both these stations the downward-increasing salinity thus counteracts the increase in specific volume caused by warming of the water and the decrease in salinity in the upper layers. Table 1 moreover shows that the effect of depth at a station on the result is not large. The data for Isokari and Märket are significant in this respect.

It may also be seen from Table 1 that the influence of variations in water density on total fluctuations of sea level is fairly slight. This in fact involves less than 10 % of the range of the monthly means, which along the Finnish coast varies between 24 and 33 cm. The data in Table 1, which are only based on observations made the first day of each month, are not representative of conditions prevailing during the entire month. Thus, during months when the water rapidly grows warmer or cooler, the

TABLE 1
Variations in sea level (cm) due to fluctuations in water density as of the first day of each month
(Datum level 20 metres)

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Ulkokalla	—0.2	—0.2	—0.3	—0.2	—0.2	—0.2	0.2	0.7	0.6	0.2	—0.2	—0.2
Isokari	—0.7	—0.5	—0.4	—0.5	—0.5	—0.3	0.6	1.5	1.4	0.4	—0.3	—0.7
Märket	—0.6	—0.7	—0.6	—0.4	—0.4	—0.4	0.4	1.6	1.5	0.4	—0.4	—0.5
Jungfruskär	—0.7	—0.6	—0.5	—0.5	—0.6	—0.5	0.5	1.6	1.5	0.6	—0.2	—0.6
Utö	—0.7	—0.6	—0.6	—0.6	—0.5	—0.2	0.8	1.6	1.3	0.3	—0.3	—0.7
Russarö	—0.6	—0.7	—0.7	—0.4	—0.1	0.2	0.9	1.3	0.8	0.0.	—0.3	—0.5
Tammio	—0.3	—0.5	—0.6	—0.3	—0.2	—0.2	0.5	1.2	1.0	0.2	—0.4	—0.4
Seivästö	—0.3	—0.4	—0.6	—0.1	—0.9	—0.6	0.3	1.0	1.1	0.7	0.1	—0.3

TABLE 2
Monthly mean variations in sea level (cm) due to fluctuations in water density.
(Datum level 20 metres)

Station	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Amplitude
Isokari	—0.6	—0.5	—0.4	—0.5	—0.4	0.0	1.1	1.5	0.9	0.0	—0.5	—0.7	2.2
Märket	—0.6	—0.6	—0.5	—0.4	—0.4	—0.1	1.1	1.7	1.0	0.1	—0.4	—0.5	2.3
Tammio	—0.4	—0.5	—0.4	—0.3	—0.2	—0.1	0.9	1.2	0.6	—0.2	—0.4	—0.3	1.7
Mean	—0.5	—0.5	—0.4	—0.4	—0.3	—0.1	1.0	1.5	0.8	0.0	—0.4	—0.5	2.1

difference becomes considerable. To eliminate this error, the specific volume as well as corresponding variations in sea level were determined every ten days at three stations : Isokari, Märket and Tammio. The results of these calculations are shown in Table 2. A comparison of the data in Table 2 with the corresponding figures in Table 1 shows that it was only in June, July, September and October that a more notable change took place. The maximum difference during these months respectively amounted to 0.3, 0.7, — 0.5 and — 0.4 cm.

It should moreover be pointed out in this connection that in every individual case, especially as regards the coastal area, variations in sea level caused by fluctuations in water density may be slightly more marked than they appear from the data in Table 2. The decrease in density is not proportional to the increase in temperature, and thus gives rise to a discrepancy in cases where determination of density is based on temperature averages. Moreover temperatures attain their highest values in the immediate vicinity of the coast, where all the tide gauges are, thus also affecting the result. In addition allowance must be made for the coastal effect on salinity variations.

For the purpose of studying the influence of different datum levels on the fluctuations in sea level due to variations in water density, Table 3 was computed. In this table we find the average value of such fluctuations at Märket for the first, eleventh and twenty-first days of each month, assuming that the datum level is at 10, 20, 30 ... 90 or 100 metres in depth. Table 3 shows that the range of these variations reaches a maximum for layers of 30 to 40 metres depth, whereas the influence of salinity becomes increasingly marked as one moves downwards to the lower layers. The ranges for the different datum levels are as follows :

10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m.
1.5 cm	2.5 cm	2.8 cm	2.8 cm	2.6 cm	2.4 cm	2.3 cm	2.1 cm	1.9 cm	1.8 cm

If we take the Märket data as being representative of conditions throughout the Baltic, and the latter's average depth as 60 metres, we can evaluate the average range of variations in sea level caused by density fluctuations as 2.4 cm. This range differs very slightly from the 2.5-cm range at the 20-metre depth selected as a datum level.

The results of our research show that variations in sea level are only in small measure due to fluctuations in water density. It may nevertheless be of interest to examine the manner in which elimination of the effect of density variations influences the remainder of the result. To this end we determined the harmonic constants of the annual and semi-annual constituents at Hangö, taking as a basis the monthly means of the 1888-1957 tidal records, using first the original figures, then the same figures corrected for density effect. The results in the first case are :

Sa : range 10.0 cm, phase lag 216°
Ssa : range 4.3 cm, phase lag 249°

and in the second case :

Sa : range 9.7 cm, phase lag 211°
Ssa : range 4.1 cm, phase lag 248°

In the second case, the sum of the ranges can be shown as decreasing by 0.5 cm, and the maximum of the annual constituent as occurring five days earlier. The elimination of the density effect hence does not

TABLE 3

Variations in sea level (cm) at Märket, due to fluctuations in water density, for various datum levels

Date		10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m
I	1	—0.3	—0.6	—0.7	—0.7	—0.5	—0.5	—0.4	—0.3	—0.2	—0.2
	11	—0.4	—0.6	—0.7	—0.7	—0.6	—0.6	—0.5	—0.4	—0.3	—0.2
	21	—0.4	—0.6	—0.8	—0.8	—0.6	—0.6	—0.5	—0.5	—0.4	—0.3
II	1	—0.4	—0.7	—0.8	—0.8	—0.7	—0.7	—0.6	—0.5	—0.5	—0.4
	11	—0.4	—0.7	—0.8	—0.8	—0.7	—0.7	—0.6	—0.5	—0.5	—0.4
	21	—0.4	—0.6	—0.8	—0.8	—0.7	—0.7	—0.6	—0.5	—0.4	—0.4
III	1	—0.4	—0.6	—0.7	—0.7	—0.6	—0.6	—0.5	—0.4	—0.4	—0.3
	11	—0.3	—0.5	—0.6	—0.7	—0.6	—0.6	—0.5	—0.4	—0.4	—0.3
	21	—0.3	—0.5	—0.6	—0.6	—0.5	—0.5	—0.4	—0.4	—0.4	—0.2
IV	1	—0.3	—0.4	—0.5	—0.5	—0.4	—0.4	—0.4	—0.4	—0.4	—0.2
	11	—0.2	—0.4	—0.5	—0.5	—0.4	—0.4	—0.4	—0.4	—0.4	—0.2
	21	—0.2	—0.4	—0.4	—0.5	—0.4	—0.5	—0.5	—0.5	—0.5	—0.3
V	1	—0.2	—0.4	—0.5	—0.5	—0.5	—0.6	—0.6	—0.5	—0.5	—0.5
	11	—0.3	—0.4	—0.5	—0.5	—0.6	—0.7	—0.7	—0.7	—0.7	—0.6
	21	—0.2	—0.4	—0.5	—0.5	—0.6	—0.7	—0.7	—0.7	—0.7	—0.7
VI	1	—0.2	—0.4	—0.4	—0.5	—0.5	—0.7	—0.7	—0.7	—0.7	—0.7
	11	—0.1	—0.2	—0.2	—0.3	—0.4	—0.5	—0.6	—0.6	—0.6	—0.6
	21	0.1	0.0	0.0	0.0	—0.1	—0.3	—0.3	—0.4	—0.4	—0.4
VII	1	0.3	0.4	0.4	0.3	0.3	0.1	0.0	—0.1	—0.1	—0.1
	11	0.5	0.9	0.9	0.8	0.7	0.5	0.4	0.3	0.3	0.2
	21	0.8	1.3	1.4	1.3	1.2	1.0	0.9	0.8	0.6	0.6
VIII	1	1.0	1.6	1.8	1.7	1.6	1.3	1.2	1.0	1.0	0.9
	11	1.1	1.8	2.0	1.9	1.8	1.5	1.4	1.2	1.1	1.0
	21	1.1	1.7	2.0	2.0	1.9	1.7	1.6	1.4	1.2	1.1
IX	1	0.9	1.5	1.8	1.8	1.6	1.4	1.3	1.1	0.9	0.8
	11	0.6	1.1	1.4	1.4	1.4	1.2	1.0	0.9	0.7	0.6
	21	0.4	0.7	1.0	1.0	1.0	0.9	0.8	0.6	0.5	0.3
X	1	0.2	0.4	0.5	0.6	0.7	0.6	0.5	0.4	0.3	0.2
	11	0.0	0.0	0.1	0.3	0.4	0.3	0.3	0.3	0.2	0.1
	21	—0.2	—0.2	—0.2	0.0	0.2	0.2	0.2	0.2	0.2	0.1
XI	1	—0.2	—0.4	—0.3	—0.2	0.0	0.0	0.2	0.2	0.2	0.2
	11	—0.3	—0.4	—0.4	—0.3	—0.1	0.0	0.1	0.2	0.3	0.3
	21	—0.3	—0.4	—0.5	—0.4	—0.2	—0.1	0.0	0.2	0.2	0.3
XII	1	—0.3	—0.5	—0.6	—0.5	—0.3	—0.2	0.0	0.1	0.2	0.2
	11	—0.3	—0.5	—0.6	—0.5	—0.3	—0.3	—0.1	0.0	0.1	0.2
	21	—0.3	—0.5	—0.6	—0.6	—0.4	—0.4	—0.2	—0.2	—0.1	0.0

TABLE 4

Monthly means of sea level calculated
through use of harmonic constants Sa and Ssa and observed means (cm)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Sa	0.2	— 4.8	— 8.6	— 10.0	— 8.8	— 5.2	— 0.2	4.8	8.6	10.0	8.8	5.2
Ssa	4.0	3.3	— 0.7	— 4.0	— 3.3	0.7	4.0	3.3	— 0,7	— 4.0	— 3.3	0.7
Total	4.2	— 1.5	— 9.3	— 14.0	— 12.1	— 4.5	3.8	8.1	7.9	6.0	5.5	5.9
Observé	4.2	— 1.4	— 10.9	— 11.5	— 13.4	— 4.6	4.2	7.8	7.8	6.6	3.7	7.5
Ecart	0.0	— 0.1	1.6	— 2.5	1.3	0.1	— 0.4	0.3	0.1	— 0.6	1.8	— 1.6

TABLE 5

Monthly means of sea level calculated
through use of harmonic constants Sa and Ssa and observed means corrected
for effect of variations in water density (cm)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Sa	1.0	— 4.0	— 7.9	— 9,6	— 8.8	— 5.7	— 1.0	4.0	7.9	9.6	8.8	5.7
Ssa	3.8	3.1	— 0.8	— 3.8	— 3.1	0.8	3.8	3.1	— 0.8	— 3.8	— 3.1	0.8
Total	4.8	— 0.9	— 8.7	— 13.4	— 11.9	— 4.9	2.8	7.1	7.1	5.8	5.7	6.5
Observé	4.7	— 0.9	— 10.5	— 11.1	— 13.1	— 4.5	3.2	6.3	7.0	6.6	4.1	8.0
Ecart	0.1	0.0	1.8	— 2.3	1.2	— 0.4	— 0.4	0.8	0.1	— 0.8	1.6	— 1.5

appreciably influence the harmonic constants. But this elimination does constitute a step towards solving the causes of annual fluctuations in the level of the Baltic. If we reproduce the seasonal variations in sea level in the Hangö area by using the harmonic constants indicated above, and compare them with the observed figures, the results in the first case are those appearing in Table 4, and in the second case those in Table 5. It will be noted that the difference is reduced after elimination of the density effect for nearly all those months during which it was most heavily marked. This proves the importance of allowing for fluctuations in water density during investigations of sea level variations in the Baltic.

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