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SALINITY VARIATIONS AS AN INDICATOR OF THE RATE OF WATER TRANSPORT ALONG THE EAST COAST OF THE BOTHNIAN SEA

by

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Abstract

The rate at which the water masses proceed along the Finnish side of the Bothnian Sea is attempted to evaluate by studying the fast and irregular salinity changes recorded at the both ends of this basin. The discussion of the results in terms of the sea level differences and some hydrometeorological conditions supports the usefulness of the method proposed.

1. *Introduction*

According to the general circulation pattern of the Baltic Sea the resultant water transport along the east coast of the Bothnian Sea is directed from the Archipelago to the Quark. On the other hand it is known, that the saline North Sea water does not enter into the Baltic as a continuous water flow, but as more or less irregular pulses of saline water. Despite the continuous mixing processes the water masses when arriving to the Northern Baltic are different in salinity. It is rather easy to follow the penetration of the largest inflows of saline water into the Baltic proper (*e.g.*, [1]).

The purpose of this paper is to study the possibilities of using the irregular salinity changes observed at the fixed oceanographic stations as an indication of the progress of water masses along the east side of the Bothnian Sea.

The working hypothesis includes the assumption that fast changes in the salinity when the water masses are entering into the Bothnian Sea are followed by corresponding changes in the Quark after reasonable time intervalls. This procedure can be compared with the evaluation of the phase difference in wave motion. This »phase difference» is inversely proportional to the rate at which the water transport takes place.

The above idea, clear and simple in principle, is interfered with, for instance, by the following factors.

i) The currents carrying out the water transport are not constant. Even reverse current directions are possible during shorter periods of time.
ii) The water fluctuates back and forth especially at the narrows, which separate the Bothnian Sea from the Baltic Proper and from the Bothnian Bay.
iii) The continuous mixing which includes large scale horizontal swirls, may cause considerable changes in the salinity of the moving water masses.

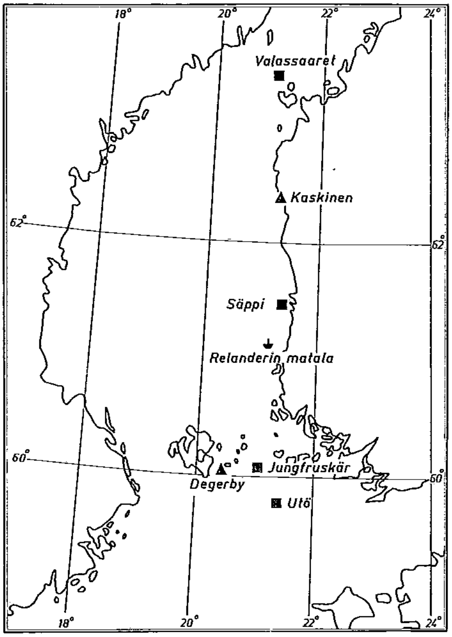

Fig. 1. The stations. ■ salinity observations, △ sea level recordings, ↓ current observations.

Further it is necessary to be sure that the possibility of simultaneous fluctuations back and forth at different stations are excluded.

2. *Material and its treatment*

The material on which this study is based consists of the regular observations from the stations Utö and Valassaaret during the years 1939—1959 (Fig. 1.). The depths were 40 m and 10 m, respectively. As a reference to which the actual salinity values are compared, the smoothed mean values corresponding to the date of observation as given by GRANQVIST [2] were used. This mean value, ($\bar{S}$), was subtracted from the actual value of salinity (S) and the difference designated by $\triangle S$. The values of $\triangle S$ were plotted against the time coordinate, the maxima and minima corresponding to each other were suggested and the time difference calculated. The rate of the water transport is the distance between the stations divided by the time interval. For the years 1952—53 the salinity variations at two additional stations, Jungfruskär and Säppi, located between the stations Utö and Valassaaret, were studied. Figs. 2 and 3 show the whole material.

The results are shown in Tables 1 and 2 and in Figs. 4 and 5, in which the transport rates are plotted *vs.* time. As the time of transport the date halfway between the endpoint of the time interval is used.

The original data are taken from the publications of this Institute, the Finnish Meteorological Office and the Hydrological Office, Helsinki, Finland.

3. *Discussion*

Firstly it should be noted that according to Figs. 2 and 3 the salinity variations at different stations in most cases are not simultaneous.

The results obtained for the rate of the water transport from Utö to Valassaaret vary from the value 2.6 cm/s to the value of 6.2 cm/s. The values are thus of a reasonable order. PALMÉN [3] reports values up to 5.4 cm/s for the annual resultant current obtained at L/V Relanderinmatala (*cf.*, Fig. 1.) AHLNÄS [4] gives a mean value of 3.4 cm/s estimated from the effects of five large inflows of North Sea water through the Danish Sounds on the salinity at Utö.

From Fig. 4 it is obvious that no systematic seasonal trend in variation of transport rates can be seen.

Table 1. The values of the water transport rate from Utö to Valassaaret. The first column gives the date halfway between the endpoint dates. The second column gives the value of the transport rate in centimeters per second.

1939

date	v
11.4	3.0
30.4	3.0
17.5	3.1
2.6	3.3
21.6	3.3
12.7	3.9
7.8	4.3
26.8	3.6
10.9	3.6
28.9	3.7
8.10	3.6
18.10	3.6
28.10	3.5
6.11	3.6
16.11	3.6
27.11	3.6
13.12	3.3
24.12	3.6
mean	3.5

1940

20.1	4.0
6.6	4.3
19.7	3.7
4.8	4.0
12.8	4.0
16.9	3.9
3.10	3.4
18.10	3.7
28.10	3.5
9.11	3.5
22.11	3.4
2.12	3.4
13.12	3.4
mean	3.7

1941

date	v
26.1	4.4
26.2	3.7
19.3	3.6
6.4	3.7
24.4	3.4
11.5	3.4
22.5	3.4
23.6	4.0
13.7	4.0
15.8	4.1
16.9	5.2
4.10	4.4
11.10	4.7
28.10	4.7
6.10	4.4
16.11	4.4
1.12	4.8
mean	4.2

1942

6.1	4.3
6.2	3.7
17.3	3.7
23.6	2.9
16.8	2.9
7.9	2.8
17.9	2.8
24.10	2.7
3.11	2.6
27.12	2.8
mean	3.1

1943

date	v
3.4	2.9
24.4	3.0
24.5	3.0
3.6	3.0
29.6	3.1
12.7	3.0
5.8	3.2
22.8	3.1
24.9	3.3
7.10	3.1
mean	3.1

1944

25.3	3.5
18.4	3.7
28.4	3.7
13.5	3.4
18.6	3.0
6.7	4.0
21.8	3.0
13.9	3.3
11.10	3.4
10.12	4.4
mean	3.5

1945

20.2	6.0
8.4	5.5
12.5	4.8
12.6	3.8
27.6	3.7
7.7	3.7
18.7	3.8
4.8	4.2
2.9	4.5
mean	4.6

(Table 1. cont.)

1946

date	*v*
20.2	4.7
11.5	3.9
19.6	4.0
4.7	4.0
28.7	4.3
5.8	4.5
17.8	5.2
7.9	4.2
17.9	4.3
6.10	4.4
23.11	4.1
10.12	4.5
22.12	4.7
mean	4.4

1947

7.1	4.4
28.1	4.6
16.5	4.2
8.6	4.1
1.7	4.8
7.10	6.7
17.10	6.7
23.11	5.3
15.12	5.1
28.12	5.5
mean	4.9

1948

date	*v*
15.1	5.3
21.4	4.7
10.5	4.8
28.6	4.3
27.7	4.3
8.8	4.4
2.9	3.9
16.10	5.3
3.11	4.8
20.12	4.5
mean	4.6

1949

6.1	3.7
4.2	3.7
3.3	4.9
21.3	4.7
21.4	4.7
2.5	4.9
12.5	4.9
22.5	4.8
2.6	4.6
28.6	3.6
18.7	3.6
1.8	3.9
25.8	4.1
6.9	4.3
19.9	4.5
26.9	4.4
8.10	3.6
16.11	3.7
6.12	4.2
mean	4.3

1950

date	*v*
22.1	4.2
3.3	4.0
27.3	4.2
17.6	5.2
5.7	5.2
7.8	5.2
18.8	5.4
1.9	6.0
27.9	5.4
11.10	5.8
21.10	5.6
10.11	5.9
4.12	4.5
17.12	4.3
mean	5.1

1951

8.1	5.3
7.2	5.6
17.4	4.3
27.4	4.2
11.5	4.1
22.5	4.0
2.7	3.8
27.7	4.3
8.8	4.4
21.8	4.6
12.9	4.8
27.10	4.3
17.11	4.2
2.12	3.9
20.12	4.3
30.12	4.0
mean	4.4

(Table 1. cont.)

1952

date	*v*
21.2	4.9
24.5	6.2
1.7	5.9
22.7	5.9
2.8	6.0
17.8	5.3
1.10	5.8
10.10	5.9
22.12	5.9
mean	5.7

1953

10.5	5.7
2.6	5.9
26.6	4.3
7.7	4.3
20.7	4.1
1.8	3.9
21.8	3.9
2.9	3.8
29.9	3.7
8.10	3.7
19.10	3.5
5.11	3.2
mean	4.2

1954

3.2	3.1
25.2	3.0
21.3	3.3
11.4	2.9
18.6	3.8
28.6	3.7
12.7	3.3
8.8	3.3
9.9	3.6
25.9	3.6
11.10	3.4
24.11	3.5
10.12	4.5
20.12	4.5
mean	3.5

1955

date	*v*
9.2	4.7
27.2	4.4
17.3	5.3
10.6	4.6
20.6	4.5
28.6	4.4
22.7	4.6
29.7	4.4
2.9	4.0
21.9	4.4
16.10	4.5
21.11	4.5
15.12	4.8
26.12	4.9
mean	4.6

1956

21.3	4.4
13.4	4.9
9.7	4.4
1.8	4.7
25.8	4.0
6.9	4.3
1.10	4.7
20.11	3.8
21.12	3.7
mean	4.3

1957

16.1	4.2
22.7	3.9
15.8	4.1
24.8	4.0
3.9	3.8
16.9	4.1
24.9	4.0
2.10	3.8
11.11	3.8
1.12	3.8
10.12	3.8
mean	3.9

1958

date	*v*
1.7	4.6
13.7	4.6
27.7	4.3
11.8	3.9
26.8	4.3
11.9	4.6
8.10	4.4
16.10	5.2
20.11	4.7
8.12	4.3
mean	4.5

1959

11.3	3.9
27.3	4.2
13.4	3.4
25.4	3.3
12.6	4.0
28.6	3.7
16.7	3.6
2.8	4.0
17.9	4.2
28.9	4.4
16.10	4.3
mean	3.9

Table 2. The values of the water transport rate between the additional stations in 1952—53. The columns as in Table 1.

1952

Utö—Jungfruskär

date	v
8.1	4.9
6.8	4.9
23.8	8.1
5.9	4.1
13.9	8.1
27.9	3.5

Utö—Säppi

date	v
25.4	12.0
1.6	10.4
25.6	8.2
24.8	5.0
7.9	6.2
16.9	6.5
27.9	6.9
6.10	7.4

Jungfurskär—Säppi

date	v
28.8	5.3
11.9	5.8
22.9	8.2
30.9	6.6
14.10	10.6
23.10	8.2
3.11	7.2

Jungfruskär—Valassaaret

date	v
24.2	5.1
4.10	5.5
16.10	6.2

1952

Säppi—Valassaaret

date	v
2.6	4.4
17.7	4.2
5.8	4.7
19.10	5.5
28.10	4.9

1953

Utö—Jungfruskär

date	v
5.4	3.8
7.5	4.1
19.5	3.8
28.5	5.4

Utö—Säppi

date	v
22.4	4.7
8.5	6.7
26.5	4.4
6.6	4.5
16.6	4.8
16.7	4.4
26.8	3.7
5.9	3.6

Jungfruskär—Säppi

date	v
26.4	6.0
1.6	4.5
12.6	4.8
20.6	4.6

Jungfruskär—Valassaaret

date	v
5.2	9.0
7.3	9.0
30.3	7.9
21.4	6.9
30.4	7.0
16.5	6.1
1.7	4.3
13.7	4.4
24.7	4.0

Säppi—Valassaaret

date	v
31.5	6.1
18.6	5.4
3.7	6.0
17.7	5.0
1.8	4.1
12.8	3.7
17.9	3.7
27.9	3.4
6.10	3.6
18.10	3.3
30.10	3.7
9.11	3.8

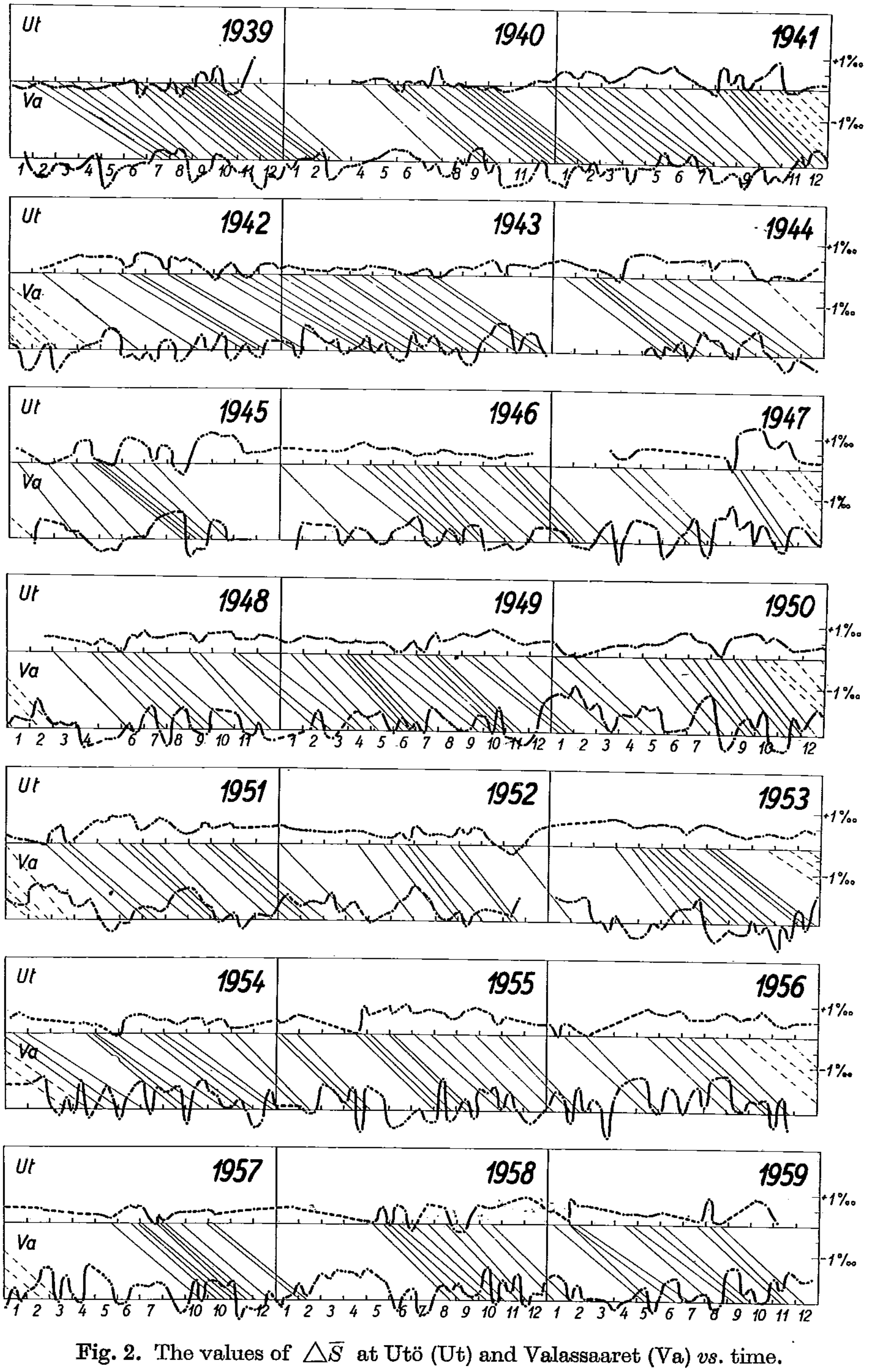

Fig. 2. The values of $\triangle\overline{S}$ at Utö (Ut) and Valassaaret (Va) *vs*. time.

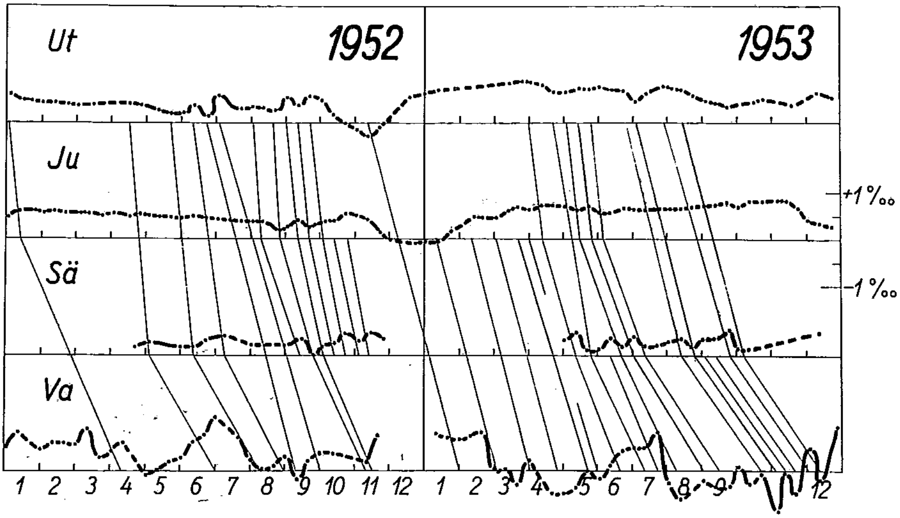

Fig. 3. The values of $\triangle\overline{S}$ at Utö (Ut), Jungfruskär (Ju), Säppi (Sä) and Valassaaret (Va) *vs.* time.

The water transport in the Baltic Sea is in greater part caused by two groups of factors. The first includes the factors affecting the water balance between the runnoff and the inflow of saline water through the Danish Sounds. The other group includes the windstew and the other effects causing temporary inclinations of the sea surface. There is, however, interdependence between these two groups of factors. The value of the transport rate may, therefore, in principle vary with almost any other property, with the salinity differences between the stations, with the discharge, with the resultant wind and with the slope of the sea surface. Considering the salinity differences no correlation can be observed.

Considering the slope of the sea surface one may expect, that the transport rate is correlated with the difference of the sea level, ($\triangle h$), at the both ends of the Bothnian Sea. Thus the transport, rate (v), should be expressed in the form of

$$v = v_1 + v_2(\triangle h)$$

where v_1 is a function of all the other factors but the sea level difference. In the most simple case there should exist a linear correlation between the transport rate and the sea level difference.

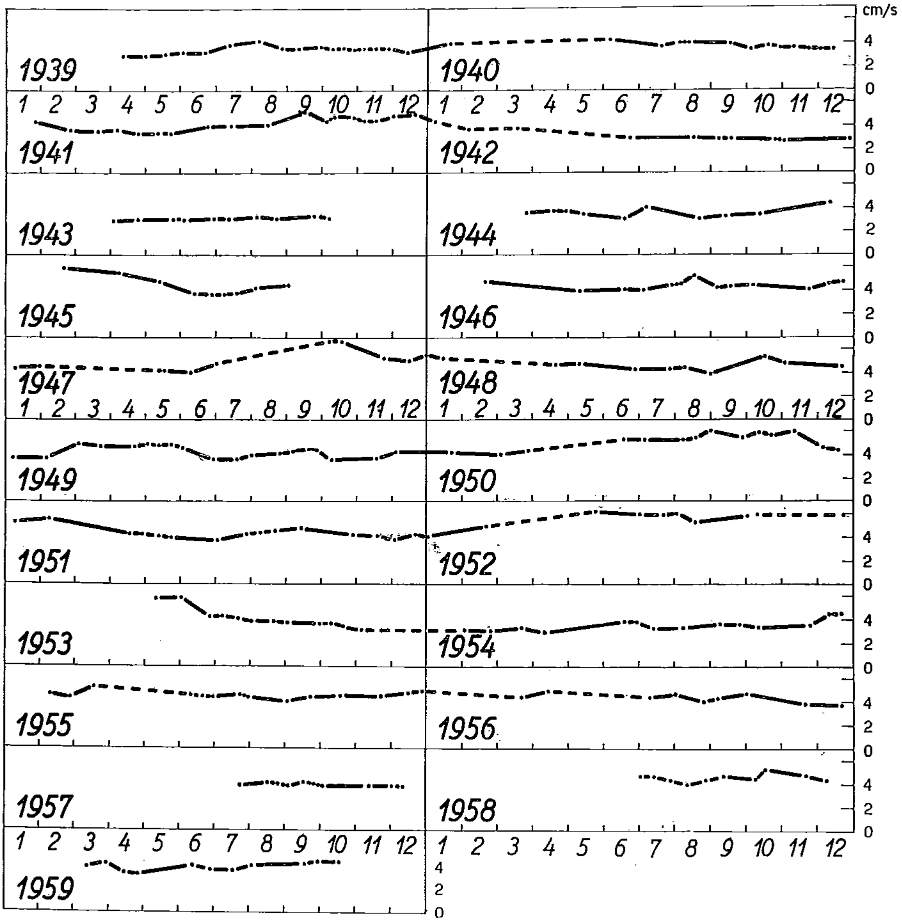

Fig. 4. The observed values of the rate of the water transport (v) between the stations Utö and Valassaaret.

$$v = v_1 + \frac{dv}{dh} \triangle h \tag{1}$$

In Fig. 6 the annual mean values of the transport rates and the sea level differences are shown (*cf.*, Table 3). In 16 cases of 21 the changes of both quantities have the same direction. In four cases one of these quantities remains constant, while the other changes and in one case only the directions are opposite. From Fig. 7 it is obvious that no correlation in the form of eq. (1) is valid for the whole period of 21 years. For several

Table 3. Data connected with the discussion. v is the annual mean value for the water transport rate from Utö to Valassaaret. $\triangle h$ is the sea level difference between both ends of the Bothnian Sea and it is obtained by subtracting the value of the annual mean sea level at Kaskinen from the corresponding value at Degerby (*cf.*, Fig. 1). MQ is the annual mean discharge of the river Kokemäki, R and α are the force and direction of the resultant wind, respectively. v_1 and dv/dh are the parameters of eq. (1).

Annual data						Data for the periods				
Year	v cm/s	$\triangle h$ cm	MQ m^3/s	R m/s	α degr.	Period	v cm/s	dv/dh 1/s	R m/s	α degr.
1939	3.5	− 0.2	159	0.55	215					
40	3.7	+ 0.2	90	0.70	236	1	3.5	0.77	0.44	257
41	4.2	+ 0.9	92	0.48	351					
42	3.1	− 0.5	88	0.87	244					
43	3.1	− 2.3	315	1.79	227	2	3.9	0.37	0.93	224
44	3.5	− 1.1	327	1.08	210					
45	4.6	+ 1.8	270	0.35	307					
46	4.4	− 1.2	118	0.70	240					
47	4.9	+ 0.5	113	0.52	289	3	4.7	0.47	0.83	245
48	4.6	− 0.3	141	1.19	255					
49	4.3	− 0.6	147	1.14	213					
50	5.1	− 0.6	196	0.55	194					
51	4.4	− 1.5	204	1.12	193	4	5.1	0.48	0.78	198
52	5.7	+ 1.2	178	0.65	210					
53	4.2	− 1.8	280	1.19	234					
54	3.5	− 1.8	232	1.20	199	(5)	(4.1)	(0.29)	0.91	218
55	4.6	+ 2.0	261	0.80	247					
56	4.3	+ 2.1	203	0.26	241	6	4.3	0.46		
57	3.9	+ 1.3	293							
58	4.5	+ 2.6	201							
59	3.9	+ 2.1	132							

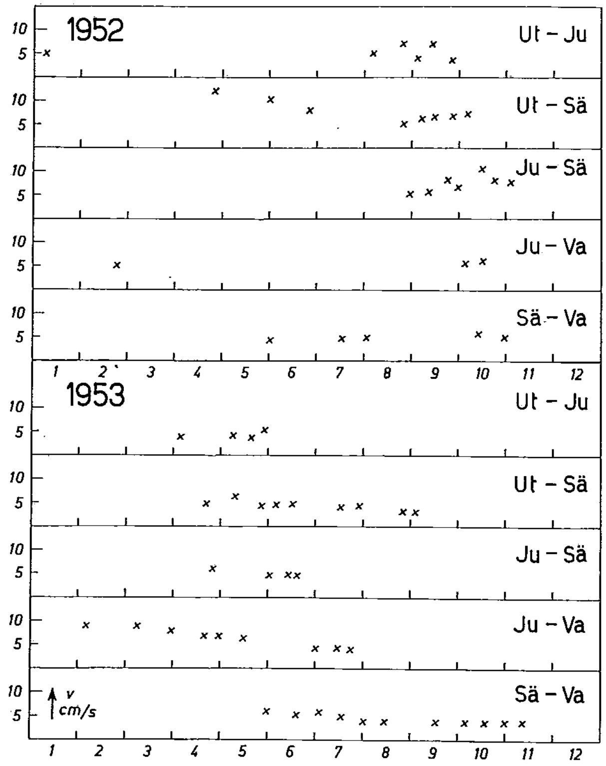

Fig. 5. The observed values of the water transport rate (v) between different stations. The symbols of the stations as in Fig. 3.

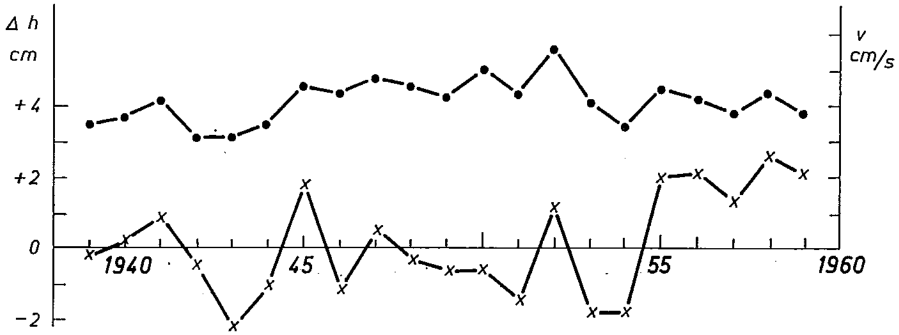

Fig. 6. The annual mean values of the water transport rates (.) and the sea level differences (x).

periods of three years, however, such a correlation seems to be evident. The values found for the parameters are given in Table 3.

The problem why the parameters of eq. (1) do vary for different periods is very complicated, but should be related to the several ways in which the meteorological conditions influence the water transport in the Baltic area. The variability and irregulativity of these conditions still increases the difficulty of the analysis of the possible factors governing the rate of water transport. A few attempts are described below.

In Table 3 there are collected data of runnoff and resultant wind. The discharge values of the river Kokemäki are chosen, since those represent about two thirds of the total discharge from the Finnish area into the Bothnia Sea [5]. The wind observations from Ilmala (Helsinki) are the only ones from which the resultant wind data are available covering the greater part of the 21 year period used in this study.

The discharge values show a clear trend to form periods, which are identical with the periods described above. In both groups there are some »transition phases» of one or two years, which are not included in any three year period. The maximum deviations from the mean discharge values during each period are

1940—42	2%
1943—45	11%
1947—49	16%
1951—53	27%
1956—58	26%

The small variation of the annual discharge values during each period indicates some kind of stability in the climatic conditions. A similar conclusion is arrived at when the severity of winters is considered. During the first period (1940—42) all winters were extremely cold and correspondingly the ice cover in the Baltic very extensive. On the other hand during the second period (1943—45) the winters were mild and only the coastal areas of the Bothnian Sea were covered by ice. The other periods are intermediates between these two extreme cases. There is, however, in the third period a continuous change from a very cold winter (1947) to a mild winter (1949), while the discharge values increase correspondingly.

The climatic features mentioned above, however, do not seem to correlate with the values of the parameters in eq. (1).

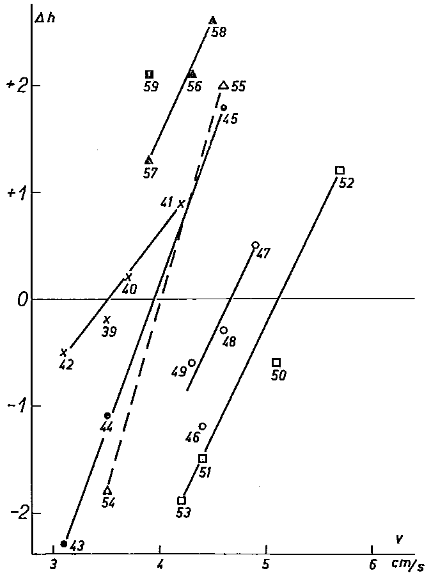

Fig. 7. Comparison of the annual mean values of the water transport rates and the sea level differences. The numbers are the two last figures of the years.

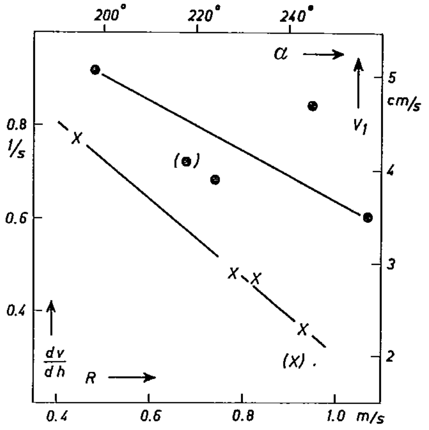

Fig. 8. Comparison of the values obtained for the parameters of eq. (1). The bracketed values correspond to the incomplete period 1954—55.
● α *vs.* v_1. x dv/dh *vs.* R.

When considering the annual wind resultants no analogous periodicity can be observed. In spite of this fact the wind resultants show some features which are worth of note. The constant term in eq. (1) has its highest value when the direction of the resultant wind is closest to the southerly, *i.e.*, most resembling the direction of the water transport, while the lowest value corresponds to the most opposite wind direction (Fig. 8.). Further the largest value of the slope in eq. (1) is found when the resultant wind force is low and the lower values when it is higher. These findings may be interpreted as follows. When the water transport is to a considerable part caused by drift currents, no greater slope of the sea surface is formed. On the other hand, when the drift currents at the surface are unfavourable to the water transport and cause a rise of the sea level in the southern end of the Bothnian Sea related to the Quark, a balancing current gaines in force.

The present material does not permit too wide generalizations. The above discussions, however, seem to show too much correlations with the external conditions, so that the method proposed for the evaluation of the rate of water transport could be thoroughly hazardeous.

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