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DETERMINATION OF THE CURRENT VELOCITY IN THE KVARK ON THE BASIS OF SEA-LEVEL RECORDS

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Abstract

Starting from sea-level records in the Bothnian Bay the current velocity in the region of the Kvark for a number of selected cases with a more or less pronounced water transport is determined with the aid of three different methods: 1° the transversal component of the surface slope (Coriolis' slope) in the Kvark, 2° the changes in mean sea-level in the Bothnian Bay, and 3° the wind stress caused piling-up of the water in the latter sea area. In spite of a considerable number of deviations the correspondence is, on an average, satisfactory.

Introduction

In a considerable number of different papers PALMÉN (compare, for instance, with [5—10]) has studied the influence of wind on the slope of the water surface in the Baltic. In these papers the emphasis is, as a rule, laid on two important and interesting problems: the piling-up of water caused by wind stress and the effect of Coriolis' force upon the wind produced currents.

Tide gauge records offer self-evidently the best starting point for a study of these problems. The choice of a suitable research area with a sufficient number of tide gauge stations is therefore very important for a successful solution to these questions. The Gulf of Bothnia with its

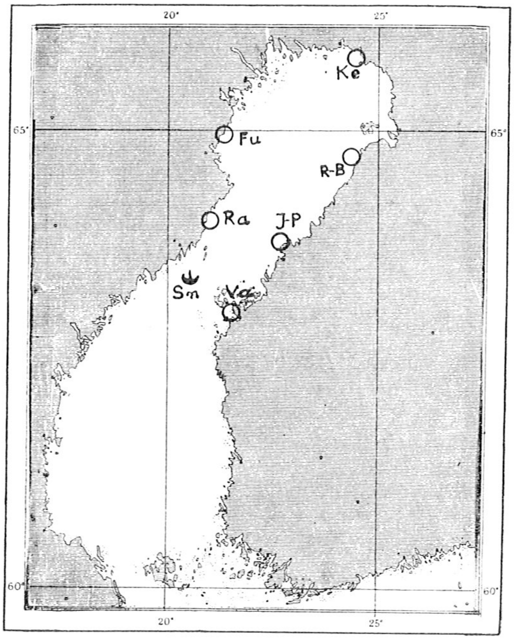

Figure 1. Location of the stations. Ke = Kemi, Fu = Furuögrund, R-B = Raahe/Brahestad, Ra = Ratan, J-P = Jakobstad/Pietarsaari, Va = Vaasa, and Sn = »Snipan».

extensive net of stations distributed comparatively uniformly over all the coasts of the sea basin fulfils these requirements fairly well (Figur 1). This Gulf consists of two pricipal parts, the Bothnian Bay in the north and the Bothnian Sea in the south connected by the narrow and shallow region of the Kvark. The current velocity in the last mentioned area may be determined in different, quite independent ways from sea-level records. Firstly, the transversal slope of the water surface caused by Coriolis' force may be used for the evaluation of the average velocity of the current. Secondly, the changes in the mean sea-level in the Bothnian Bay during the corresponding time offer a possibility of computing this current. Finally, it may be borne in mind that there exist at least theoretical means to determine the velocity of the surface current with the aid of the data for the piling-up of water due to wind stress. Palmén has deduced a formula for surface slope and wind velocity in a stationary case, on the one hand [8], and surface current velocity and wind velocity, on the other hand [6].

In an earlier paper the author determined the current velocity in the Kvark using the first two methods [3]. The research covered a continuous period of 19 days, with three data daily corresponding within the limits of one hour to the time fixed for wind observations made on board the light-ship »Snipan» with lies in the Kvark during the navigation period. As no data on atmospheric pressure were available for the first two of the three tide gauge stations Jakobstad (Pietarsaari) (63°42′ N.L., 22°42′ E.L.), Ratan (64°0′ N.L., 20°55′ E.L.) and Vasa (63°6′ N.L., 21°34′ E.L.), which formed the basis for the computing of the Coriolian slope, the only possible way to eliminate the disturbing influence of atmospheric pressure upon the sea-level was to use the relevant values determined by PALMÉN for different wind velocities [7]. It could, of course, be presumed that wind observations made on board the light-ship »Snipan» were more appropriate for this purpose than those of Vasa, where the coastal effect may, at least in some cases, produce considerable deviations. The final results were quite satisfactory. The two series representing the velocity of the current had on the whole the same rhythm and the corresponding correlation coefficient amounted to 0.807. The average deviation, however, was 4.5 $cmsec^{-1}$ which is doubtless a rather high value, especially if we take into consideration the fact that the current velocity in very few cases exceeded 10 $cmsec^{-1}$. The principal causes for these deviations must, as PALMÉN has pointed out [7], be sought not only in the numerous isles in the Kvark, but also in the considerable differences in depth between different parts of the sea area. These factors may give rise to local bottom and deep water currents which are not easy to foresee.

Selection of the cases used

For the present study it seemed appropriate to choose not a continuous series of observations, but to select for a more prolonged period cases characteristic of a marked movement and thus representing also a fairly high velocity of the current. For this purpose, the approximate value of the mean sea-level in the Bothnian Bay during the years 1948—1950 was computed with the aid of the tide gauge records, six readings a day, for Kemi (65°44′ N.L., 24°33′ E.L.,) Raahe (Brahestad) (64°42′ N.L., 24°30′ E.L.) and Ratan. As the reference level in this connexion and in all other corresponding cases was used the mean sea-level for the 30 year period 1926—1955, corrected for land upheaval. The next step was to select cases with an average change in mean sea-level of more than

15 cm during four hours. In order to obtain more exact values for the mean sea level and its changes, the records for two additional tide gauge stations in the Bothnian Bay, Furuögrund (64°55' N.L., 21°14' E.L.) on the Swedish coast and Jakobstad on the Finnish coast, were considered in these cases. The use of five stations instead of three generally reduced to some degree the extreme data for the mean sea level, causing a corresponding decrease of the values for mean sea-level changes and thus resulting also in a less pronounced velocity of the current in the Kvark. The original number of cases was 66, but about 40% of them had to be rejected, partly owing to the incompleteness of the necessary records (interpolated data of course could not be used for the determination of the transversal slope of the water surface), partly because the whole situation was too complicated or uncertain to permit general conclusions as to the prevailing wind and air pressure conditions. Too high a reduction of the changes in mean sea-level for the five stations was the cause for a few omissions.

Considering the importance of achieving as good conformity as possible with the method for determining the current velocity by means of the transversal slope of the water surface in the Kvark, it seemed appropriate to choose as a basis for the computations the section which at Ratan cuts the Swedish coast at right angles. Leaving out the shallow area in the immediate vicinity of the coast, where the current conditions may deviate comparatively much from the average, the breadth of the section is approximately 75 km and its average depth 45 m. A change in the mean sea level in the Bothnian Bay of 1 cm during four hours corresponds to a current velocity through this section of 0.7 cmsec^{-1}.

In this connexion, it may be stressed that besides the water movement through the Kvark other factors, such as the water discharge from rivers, precipitation, evaporation and variations in the density of sea water, may influence the mean sea-level in the Bothnian Bay. However, as the time between two successive records used in the following amounts to four hours only, the disturbing effect of these factors upon the results could be disregarded.

Computation of current velocity

For determination of the transversal slope of the water surface in the Kvark, the sea-level records for the tide gauge stations Ratan, Jakobstad and Vasa were used. This slope was determined graphically following a method closely described by EXNER [1]. The relation between the Coriolian slope Δh in cm per 100 km and the current velocity u in cmsec^{-1} is given by the formula:

$$\Delta h = \frac{2\omega \ u \ sin \ \varphi}{g}$$

where ω,φ and g are respectively, the angular speed of the earth's rotation, the geographic latitude and the acceleration of gravity.

Before the influence of Coriolis' force upon the water surface could be computed, the static effect of the atmospheric pressure had to be eliminated. As a considerable number of the cases used in this study refer to the winter half of the year for which no wind observations made on sea are available, the lightship »Snipan» having left owing to ice formation, the only possibility was to proceed in the following way: First, the wind velocity was estimated with the aid of the sea-level data indicating for the stations in the Bothnian Bay the piling-up of water caused by wind stress. The formula used for this purpose:

$$\Delta H = \frac{3.2 \ w^2}{d} \tag{2}$$

was given by PALMÉN [8]. ΔH indicates the piling-up of the water surface in cm per 100 km caused by wind stress, w the wind velocity in msec^{-1}, and d the average depth of the sea basin in meters. It is, of course, self-evident that the wind velocities determined in this way are approximate only, but as the air pressure corrections computed on the basis of these data using the method of PALMÉN [7] amount to a few centimetres only, the probable error is numerically not very marked. It must be borne in mind in this connexion, however, that in some cases, depending on the direction and the absolute value of the slope, the influence of one centimetre upon the final result may be considerable.

With the current velocities computed for the hours in question the mean value for two successive cases gives an idea of the average current velocity during four-hour periods. Probable changes in the movement of the water during this time will obviously not be taken into consideration in this way. This limitation must cause a number of different deviations from the data on current velocity evaluated with the aid of sea-level changes in the Bothnian Bay. These data could be expected to give a more exact picture of the average current conditions, but on the other hand they may in some cases be influenced too highly by exceptional local conditions at a certain tide gauge station. For instance, the piling-up effect at Kemi is sometimes very accentuated owing to the position of the station in the innermost shallow part of the Bothnian Bay.

There is still a third possibility left for evaluation of the current velocity in the selected cases on the basis of sea level records. According to formula (2), there exists a relation between the slope of the water surface and the wind velocity. This formula was used above to determine the distribution of atmospheric pressure. Several objections may be raised to the use of formula (2) for the determination of the current velocity. If the surface slope, for instance, is computed with the aid of the sea level records for Kemi and Jakobstad the result is the wind velocity for this area and not for the Kvark. Moreover, PALMÉN deduced his formula for a stationary case, a condition that certainly did not obtain in numerous of the present cases. The piling-up of water at Kemi may, as mentioned above, be very pronounced, causing a corresponding overestimation of wind velocity. A comparatively extensive ice cover may, on the contrary, have a reducing effect on the piling-up of water by wind stress (4). This fact, however, hardly needs to be considered here, as cases for the winter months proper refer only to the year 1949 when the winter was rather mild.

Passing over from wind velocity to current velocity, there is available PALMÉN's study [6] of the connexion between wind velocity w and surface current velocity u_0 at Finngrundet, in the south part of the Gulf of Bothnia. The original relation is

$$u_0 = 1.44\,w \tag{3}$$

but PALMÉN himself later [8] used a somewhat reduced coefficient, i.e. 1.2, which seems to be more appropriate for the present purpose, too, and on which the following results are based.

The results

The numerical results attained by the three methods are collected in Table 1. The first column of this Table indicates a period with a considerable water transport in the Kvark. The second column gives the current velocity for the corresponding hours computed on the basis of the transversal slope of the water surface, and in the third column are the mean values for the interjacent four hours. The fourth column gives the current velocities determined according to the changes in the sea-level in the Bothnian Bay, while the fifth and sixth columns are

Table 1. Current velocity (cm sec^{-1}) in the Kvark computed on the basis of the Coriolian slope (A), the changes in sea-level (B) and the piling-up of water due to wind stress (C).

Time (GMT+2^h)	A		B	C	
1948 V 4. 22^h	10.8	10.8	9.1	4.7	9.6
5. 2^h	10.8			14.4	
1948 V 25. 14^h	10.2	10.6	9.8	12.0	16.8
18^h	11.1			21.6	
1948 V 28. 10^h	7.5	7.4	8.4	3.8	10.3
14^h	7.2			16.8	
1948 IX 27. 10^h	4.2	5.2	10.5	14.4	17.4
14^h	6.3			20.4	
1948 X 22. 18^h	10.5	8.8	10.5	7.2	9.4
22^h	7.2			11.6	
1948 XI 10. 22^h	−20.4	−18.4	−11.9	−12.0	−12.6
11. 2^h	−16.5	−10.8	−12.2	−13.2	−12.6
6^h	− 5.1			−12.0	
1948 XI 13. 10^h	17.1	19.4	9.8	15.6	16.8
14^h	21.6			18.0	
1948 XI 20. 10^h	8.4	8.4	10.5	10.8	13.2
14^h	8.4			15.6	
1948 XI 30. 10^h	9.3	8.8	9.1	12.0	13.1
14^h	8.4			14.2	
1948 XII 29. 6^h	13.5	11.2	14.0	18.0	20.4
10^h	9.0			22.8	
1948 XII 31. 10^h	8.7	8.2	9.8	10.8	12.2
14^h	7.8			13.7	
1949 I 6. 6^h	8.1	9.2	11.9	9.2	12.8
10^h	10.2			16.3	
1949 I 10. 10^h	19.2	20.7	16.8	12.0	16.2
14^h	22.2	18.6	11.9	20.4	18.7
18^h	14.9	10.2	12.6	17.0	17.5
22^h	5.4			18.0	
1949 I 13. 18^h	8.4	12.3	11.2	12.8	14.9
22^h	16.2	16.5	12.6	17.0	17.7
14. 2^h	16.8			18.4	
1949 I 15. 6^h	−10.2	−11.1	−11.2	0.0	− 9.8
10^h	−12.0	−10.8	−13.3	−19.6	−21.0
14^h	− 9.6	− 9.2	−12.6	−22.4	−22.5
18^h	− 8.7	− 7.5	−12.6	−22.6	−22.5
22^h	− 6.3			−22.4	
1949 I 21. 18^h	−11.4	−11.0	−10.5	−16.8	−16.8
22^h	−10.5			−16.8	

Table 1. (Continued)

Time (GMT+2^h)				A		B	C	
1949	I	30.	18^h	−11.7	−10.4	−14.7	−13.2	−15.5
			22^h	− 9.0	− 7.8	−13.3	−17.8	−17.3
		31.	2^h	− 6.6	− 7.0	−11.9	−16.8	−16.2
			6^h	− 7.5	− 5.4	−12.2	−15.6	−15.1
			10^h	− 3.3			−14.6	
1949	II	4.	22^h	− 5.4	− 9.4	− 9.1	− 2.4	− 8.2
		5.	2^h	−13.5	−12.4	−10.5	−14.0	−14.0
			6^h	−11.4	− 8.2	−11.2	−14.0	−14.0
			10^h	− 5.1			−14.0	
1949	II	27.	14^h	−19.8	−18.3	−12.6	−10.8	−11.4
			18^h	−16.8	−13.6	−13.3	−12·0	−12.6
			22^h	−10.5			−13.2	
1949	III	22.	10^h	10.5	7.6	10.5	9.6	10.8
			14^h	4.8			12.0	
1949	IX	29.	14^h	9.0	9.9	9.1	8.4	12.0
			18^h	10.8	11.4	11.9	15.6	17.4
			22^h	12.0			19.2	
1949	X	5.	6^h	14.7	15.0	11.9	7.2	9.6
			10^h	15.4			12.0	
1949	X	19.	10^h	6.0	5.8	9.1	14.4	16.2
			14^h	5.7			18.0	
1949	X	21.	22^h	10.8	11.4	8.4	7.2	10.8
		22.	2^h	12.0			14.4	
1950	X	9.	18^h	7.5	14.2	11.9	12.0	13.8
			22^h	21.0	15.6	9.8	15.6	19.2
		10.	2^h	10.2			22.8	

evaluated with the aid of the piling-up of water caused by wind stress. A positive value in Table 1 indicates an inflow into the Kvark, a negative value an outflow.

A comparison of the current velocities computed according to the three methods shows, in spite of considerable deviations, a fairly good correspondence on the whole. In fact, the numerical mean value for current velocity determined with the aid of the first method is 11.1 $cmsec^{-1}$ the second method gives 11.3 $cmsec^{-1}$ as the mean value, and the third 14.4 $cmsec^{-1}$. The deviation in the last case is 3 $cmsec^{-1}$ in round figures, but considering the above mentioned uncertainties connected with the determination of the velocities of wind and current from the data for the piling-up of water, the result is not too bad. The values refer, moreover, to the surface current and not, as in the other cases, to the mean current velocity in the whole water column, a fact which at least to some degree may be responsible for the differences.

A few words, finally, may be said about the maximum variations in the mean sea-level in the Bothnian Bay. According to the results for the five tide gauge stations used, the highest values during the years 1948—1950 was 105 cm above the average value for this period, the lowest 95 cm below this value. The variations amounted thus to 2 m, or 5% of the total water quantity in the Bothnian Bay. As a comparison, it may be mentioned that HELA [2] using the records for the 10 year period 1926—1935, computed that the differences between the extreme values for the variations of the mean sea-level in the entire Baltic were 111 cm. The mean sea-level in the Bothnian Bay is thus, as could be extected, highly influenced by the piling-up of water due to wind stress.

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