MERENTUTKIMUSLAITOKSEN JULKAISU
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ON INTERNAL WAVES IN THE NORTHERN BALTIC

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The interesting question of the occurrence of internal waves in the Danish Sounds has been closely studied several times, especially by Swedish scientists. In this connexion reference may be made to the researches on internal waves by O. PETTERSSON, (9) ZEILON (12) and KULLENBERG (6). The Baltic, on the other hand, has not yet been examined in this respect. The principal reason for this omission is without doubt the lack of an observation material suitable for such an investigation. For instance, the Finnish hydrographical observations, which are fairly extensive in many respects, contain only two series of data that may be of some use for this purpose. In July 1914 GRANQVIST (4) spent 17 days on board the lightship »Äransgrund» (now called »Helsinki», position 59°57′ N., 24°57′ E.) in the middle part of the Gulf of Finland. GRANQVIST's observations comprised the determination of temperature and salinity six times daily at every fifth meter from the surface to a depth of 50 m, i. e. near the bottom. Eight years later, in July 1922, a joint Finnish and Swedish expedition was organised in the Archipelago and the Åland Sea (11). For the purpose of the internal waves the most important part of the hydrographical material gathered consists of the temperature and salinity data recorded on board the lightship »Storbrotten» (position 60°26′ N., 19°13′ E.), covering every fourth hour from 19 to 29 July. At this lightship too the observations were made in the upper water layers, down to 20 m, at five-meter intervals. In addition, observations were made at a depth of 30 m, i. e. somewhat above the bottom. It is self-evident that these two series are too limited temporally for a more comprehensive investigation, e.g. for the determination of the possible occurrence of internal waves with more prolonged periods. Even waves with a period of a few hours only can hardly be traced with the aid of the existing material since the observations have not been made frequently enough. It seemed appropriate therefore to confine the examination of internal waves in the Baltic to the tide wave periods and attempt to find a possible connexion between water level variations on the one hand and fluctuations in temperature and salinity on the other. As water level observations have been performed at neither Äransgrund nor Storbrotten we were compelled to use in the former case the relevant values from the automatic gauge stations on the coasts of the Gulf of Finland, in the latter case the records attained during the research period at Hellman (60°12′ N., 19°18′ E.) with the aid of a temporary self-registering tide pole. The water level material of these stations has earlier been analysed already and harmonic constants for the principal tide components have been determined for the stations in the Gulf of Finland by Witting (10) and the author (8), for Hellman by the author (7). In this connexion it may, however, be appropriate to point out that internal waves are not directly caused by tidal forces; they are, as suggested by Defant (1), occasioned by the periodic variations of the actual tidal currents which produce periodic changes in the discontinuity layers in the sea.

Beginning with the observations at Storbrotten we may at once emphasize that owing to the short research period the reciprocal disturbing influence of the different tide components cannot be eliminated; the results of the harmonic analysis must therefore be considered approximative only. Corresponding to the analysis of water level values performed earlier for Hellman the harmonic constants have been determined for the two semi-diurnal waves S_2 and M_2, and the diurnal waves K_1 and O_1, in which the constants for the former diurnal component must be considered a resultant of the three waves K_1, S_1 and P which cannot be treated separately owing to the limited research period. The observations on salinity seem on the whole to offer the most suitable data as the temperature values are doubtless influenced by the diurnal warming of the sea water, at least in the upper layers, and we must expect these variations in temperature to be reflected in the σ_t-values too.

The average salinities at Storbrotten during the research period were:

0 m	5 m	10 m	15 m	20 m	30 m
5.43 ‰	5.44 ‰	5.49 ‰	5.53 ‰	5.62 ‰	5.89 ‰

These figures show that the increase in salinity is very slight in the upper water layers down to a depth of 15 m, somewhat greater between 15 and 20 m, and reaches its maximum value between 20 and 30 m. Unfortunately no salinity observations have been made at Storbrotten at 25 m and below 30 m during the research period; but our general knowledge of the water stratification in the sea-area in question permits the assumption that the layers of the greatest salinity increase is situated not far from the bottom, probably at about 30 m deep, which may be considered a boundary layer. This assumption is very distinctly verified by the results for harmonic analysis given in Table 1.

Table 1. Harmonic constants for salinity at Storbrotten.
(H is given in S $^0/_{00}$, $\varkappa$ refers to 0^h 19 July 1922).

Depth	$(S_1 +) K_1 (+ P)$		S_2		O_1		M_2	
	H	$\varkappa$	H	$\varkappa$	H	$\varkappa$	H	$\varkappa$
0 m ..	0.010	354°	0.009	21°	0.007	90°	0.005	68°
5 m ..	0.004	333°	0.005	292°	0.010	127°	0.006	81°
10 m ..	0.012	318°	0.006	351°	0.012	138°	0.015	212°
15 m ..	0.006	51°	0.002	63°	0.023	88°	0.005	248°
20 m ..	0.015	11°	0.007	304°	0.009	252°	0.018	131°
30 m ..	0.019	342°	0.052	270°	0.006	51°	0.039	120°

A rapid glance at the table shows immediately that in two cases the amplitudes are considerably greater than in the remaining ones, viz. the semi-diurnal components S_2 and M_2 at 30 m. In the former case the amplitude is about 2.2 times greater than the third greatest amplitude (0.023 $^0/_{00}$), in the latter 1.7 times. The salinity amplitudes of 0.052 $^0/_{00}$ for S_2 and 0.039 $^0/_{00}$ for M_2 correspond to amplitudes of of internal waves of about 2 m and 1.5 m respectively. Owing to the shortness of the research period the amplitudes can, however, only be considered approximative. In the upper water layers with slight salinity changes it would certainly be possible to compute from Table 1 and the average salinities for different depth an internal wave with an amplitude of about the same or an even greater magnitude, but owing to the small values of the salinity amplitudes these results have to be treated with reserve. The rule deduced for simplified conditions, according to which the amplitudes of internal waves decrease linearly from the boundary layer to the free surface and to the bottom, could not thus be proved in this case. It must, moreover, be borne in mind that the observed variations are not always due to vertical displacements only; they may, at least to some degree, depend upon the horizontal motion of heterogeneous water masses. The variations of the phase angle with the depth for the different components show no distinct regularity, which helps to prove the above. That horizontal dislocations of the water masses have taken place seems to be verified likewise by the harmonic analysis of the temperature values. As, contrary to salinity, temperature decreases with the depth, the phase angles for the two elements ought in order to represent the same internal wave deviate 180° from each other. This, however, is not the case as a rule as Table 2 shows. Besides the values for H and $\varkappa$ Table 2 gives the differences between the values for the phase angles for temperature and salinity.

To complement Table 2 we give in the following the average temperatures for different depths at Storbrotten during the research period:

0 m	5 m	10 m	15 m	20 m	30 m
13.3°	12.6°	10.9°	7.4°	5.4°	3.7°

Table 2. Harmonic constants for temperature at Storbrotten.
(H is given in degrees centigrade, $\varkappa$ refers to 0^h 19 July 1922, $\triangle$ is the difference between the temperature and salinity values for the phase angles).

Depth	$(S_1 +) K_1 (+ P)$			S_2			O_1			M_2		
	H	$\varkappa$	$\triangle$	H	$\varkappa$	$\triangle$	H	$\varkappa$	$\triangle$	H	$\varkappa$	$\triangle$
0 m ..	0.35	252°	—102°	0.09	155°	132°	0.21	194°	104°	0.05	292°	—136°
5 m ..	0.11	225°	—108°	0.15	217°	— 75°	0.12	180°	53°	0.06	81°	0°
10 m ..	0.44	232°	— 86°	0.04	166°	175°	0.34	197°	59°	0.20	297°	85°
15 m ..	0.42	265°	—146°	0.18	146°	85°	0.22	106°	18°	0.48	10°	122°
20 m ..	0.04	105°	94°	0.10	108°	164°	0.12	194°	—58°	0.18	315°	—178°
30 m ..	0.19	242°	—100°	0.04	96°	180°	0.11	139°	88°	0.15	258°	138°

The columns $\triangle$ in Table 2 show that the condition for the confirmation of salinity results by temperature data is on the whole not fulfilled. The agreement is least satisfactory for the two diurnal components which, as above mentioned, are influenced by the diurnal warming of the sea water. It is also these waves which as a rule show the largest amplitudes, but, of course, no greater importance may be attributed to this fact for the purpose of internal waves. Concerning the semi-diurnal component S_2 the agreement for the phase angles is quite good for three depths, but the calculated amplitudes for the internal waves in question do not give as satisfactory results. We get the following values for the amplitudes of the internal waves over a 12-hour period using temperature observations and salinity data:

	t^0	S ‰
10 m	0.07 m	0.66 m
20 m	0.20 m	0.32 m
30 m	0.24 m	1.93 m

Except at 20 m deep where both amplitudes are of the same magnitude, the pictures given by the two elements are highly deviating, salinity giving results 8 to 9.5 times greater than those given by temperature. In this connexion it is only, however, the depth of 30 m that is of noteworthy interest because, as mentioned above, no greater importance can be attributed to the other depths. The considerable difference in this case may be explained by the existence of a horizontal motion of water masses of such a consistency that they influence the vertical displacement due to internal waves quite differently as far as temperature and salinity are concerned.

The harmonic analysis of the corresponding values for σ_t calculated for the same constituents and depths does not, as was to be expected, give us anything substantially new. The phase angles generally agree satisfactorily with those for temperature (difference 180°), but the amplitudes are in the most cases small and hence unreliable. Greater amplitudes

($>$ 0.02) are noted mainly for the diurnal waves in the upper layers where they are connected with the periodic warming of the water. Moreover, the amplitudes are 0.043 and 0.029 for S_2 and M_2 respectively at a depth of 30 m, distinctly reflecting the corresponding results for salinity.

Passing over to the harmonic constants for the water level at Hellman we reproduce the following values determined earlier (7). They are given in mm and refer to the same initial time as in Tables 1 and 2.

$(S_1+)K_1(+P)$		S_2		O_1		M_2	
H	$\varkappa$	H	$\varkappa$	H	$\varkappa$	H	$\varkappa$
13.2	118°	7.8	255°	5.0	216°	3.7	105°

Comparing these values with those for salinity at 30 m we note a striking agreement between the phase angles for S_2 and M_2. The deviation amounts in both cases to 15°, corresponding to a time difference of about half an hour. This seems to indicate the close relationship between tides and internal waves. In this connexion it may be appropriate to mention DEFANT's (2) results for the southern part of the Kattegat: The phases of the tidal wave and the internal wave coincide entirely at his research spot. The difference of a round half-hour in our case may be ascribed to the fact that the hydrographical observations and the water level records have been made at two different places about 25 km apart. On the other hand the ratio of the amplitudes of the internal wave and the tidal wave seems to be considerably greater in the Baltic than in the Kattegat. While DEFANT gives a ratio in round figures of 100, we make the amplitude of the internal wave for S_2 about 250 times greater than that of the tidal wave, for M_2 the corresponding ratio being almost 400.

It has already been mentioned that the tidal currents must be considered responsible for the occurrence of internal waves. It may therefore be interesting to examine whether other periodic currents evoke internal waves too. KAIPIAINEN (5), when working on the current material for Storbrotten during the research period, verified an inertia current which lasted for 85 hours, i. e. from 23^h the 21 July to 12^h the 25 July. The harmonic analysis for the salinity observations at 30 m during the corresponding time gives (using the theoretic period of 13.8 hours) an amplitude of 0.067 ‰, which means that the amplitude of the internal wave amounts to practically 2.5 m. If the research period is analysed in its entirety the amplitude decreases considerably becoming 0.026 ‰. The time for the appearance of the maximum remains relatively unchanged, showing a dislocation of 0.7 hours only. This proves the close connexion between the inertia current and the internal wave in question. It may be appropriate to emphasize once more the shortness of the research period which makes the result uncertain and means that it could have been influenced, at least to some degree, by other waves with semi-diurnal periods.

Before we begin to examine the material for Äransgrund a few words are called for on the general stratification of the water in the Gulf of Finland. There is in this respect a considerable difference from conditions in the region around Storbrotten. At Äransgrund there is no such rather abrupt increase in salinity as was noted at Storbrotten at a depth of about 30 m, i. e. there is no marked boundary layer. This does not mean, however, that the increase in salinity as such is less in the Äransgrund region of the Gulf of Finland than in the area around Storbrotten. On the contrary, the stratification at the former station is more stable than at the later as can be seen from the following figures for the average salinity at Äransgrund during the research period:

0 m	5 m	10 m	15 m	20 m	25 m	30 m	35 m	40 m	45 m
5.61	5.65	5.84	6.00	6.12	6.28	6.45	6.65	6.85	7.02 ‰
△	0.04	0.19	0.16	0.12	0.16	0.17	0.20	0.20	0.17 ‰

The last row in the above table gives the salinity increase between two successive depths with 5 m intervals between them. We note two maxima, the first between 5 and 10 m, the second between 30 and 40 m. With the exception of the surface layer the general course of the salinity increase is, however, fairly even. Of course, the decrease in temperature towards the bottom influences this picture considerably, but on the whole there is no denying the difference between the conditions at Storbrotten and Äransgrund. In place of one marked discontinuity layer several boundary layers can be noted in the Gulf of Finland. According to FJELDSTAD (3) this means that several internal waves may occur simultaneously, and obviously the greater the number of boundary layers the greater the number of possible internal waves. As result we have a very complicated picture with a practically unlimited number of internal waves in all the cases where the density varies continuously with the depth. But the amplitudes of these waves are not very large, the level of the maximum amplitudes is distinctly marked, and sounding at certain given depths only does not suffice to prove the occurrence of possible internal waves. Table 3 where we find the harmonic constants of the internal waves for the two components (S_1 +) K_1 (+ P) and S_2 confirms this.

A glance at the table shows that the amplitudes are as a rule smaller than 0.02 ‰. They all correspond, with the exception of the surface waves, to an internal wave amplitude of less than 0.75 m, in ten cases less than 0.5 m. As a general feature it may be mentioned that the amplitudes of the S_2-wave are considerably smaller than those of the K_1-wave. The same tendency could be noted at Storbrotten too, although the depth of 30 m forms a marked exception in this connexion. An explanation of this phenomenon may perhaps be sought in the fact

Table 3. Harmonic constants for salinity at Äransgrund.
(H is given in S $^0/_{00}$, $\varkappa$ refers to 0^h 11 July 1914).

Depth	$(S_1 +) K_1 (+ P)$		S_2	
	H	$\varkappa$	H	$\varkappa$
0 m ..	0.009	348°	0.009	223°
5 m ..	0.012	46°	0.012	314°
10 m ..	0.026	212°	0.014	145°
15 m ..	0.015	23°	0.009	43°
20 m ..	0.014	0°	0.017	41°
25 m ..	—	—	0.007	64°
30 m ..	0.018	282°	0.006	30°
35 m ..	0.019	283°	0.014	39°
40 m ..	0.018	308°	0.012	16°
45 m ..	0.016	301°	0.006	331°

that the diurnal tide waves in the region in question have on the whole greater amplitudes than the semi-diurnal waves. As to the phase angles, it is difficult to reach general conclusions. For the semi-diurnal wave, in spite of several deviations, a delay from the bottom to the surface may be noted. As the S_2-tide wave forms an anti-clockwise amphidromie in the Gulf of Finland it is not impossible that some connexion exists between the phase angles of the tide wave and those of the internal waves. When the maximum of the tide wave reaches the meridian of Äransgrund on the south coast of the Gulf of Finland the salinity at a depth of about 45 m is at its highest; when the top of the S_2-tide is observed in the inner parts of the Gulf the maximum salinity is noted at depths between 15 and 10 m; and, finally, the maxima coincide with the tide wave at the north-west coast and salinity values in the upper layers. The material under consideration is, however, too limited to allow definite conclusions. It is still more difficult to get general results for the diurnal wave. The only characteristic is the approximative constancy of the phase angles in the deeper layers, from the bottom up to a depth of 30 m.

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