INTERNAL WAVES IN SCANDINAVIAN WATERS

by

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In the summer of 1907 Otto Pettersson on board the Swedish research ship " Skagerak " studied the exchange of water between the Baltic and the Kattegat which takes place through the Great Belt. From the anchored ship hydrographic soundings from surface to bottom and also current measurements were repeatedly made. The sharply developed boundary or transition-layer between the outgoing surface current of brackish water from the Baltic and the ingoing undercurrent of salt sea-water from the Kattegat was found to display vertical displacements of considerable amplitude, in which the main tidal period of 12 1/2 hours was manifest. In the following summer these measurements were repeated by G. Ridderstad with very similar results. On the strength of this evidence Otto Pettersson suggested that the tides, which are very faint in the surface, occur instead in the transition-layer as boundary tides with vertical movements of several metres.

Leading oceanographers of 30 years ago were in general sceptical about any occurrence of such boundary tides. Thus O. Krümmel in his wellknown " Handbuch der Ozeanographie " accepts the alternative explanation offered by E. M. Wedderburn, according to which the internal movements discovered by Pettersson are due to an internal seiche of the water within the Great Belt itself, having a period of roughly 24 hours. Subsequent observations by other Scandinavian oceanographers have, however, confirmed Pettersson's explanation and shown that similar movements of tidal character occur also in other parts of the ocean as in the Kattegat, the Straits of Gibraltar etc.

Encouraged by these results in the Belts, Otto Pettersson subsequently started regular observations of boundary movements in the Gullmarfjord, west coast of Sweden, where the hydrographic station Bornö, built by himself and Ekman in 1902, offers unique opportunities for similar studies. An observation pier nearly 20 metres in length, depending from a steep rock, projects over the waters of the fjord, allowing hydrographic soundings down to depths exceeding 30 metres to be taken independent of the weather conditions, ice, fog, etc. Such soundings, affording values of the temperature and the salinity in every 5th metre from surface to bottom have, with certain breaks, been carried out daily since 1909. The results from these observations proved that very large upheavals and subsidences of the different water strata occur in the fjord, so that in the course of one or two days a certain isohaline surface may rise or fall by 10 to 20 metres or even more. Since the free water-surface in the fjord remains almost stationary or becomes displaced by decimetres only, the boundary movements involve horizontal currents of a compensatory character, transporting hundreds of millions of cubic metres of one layer out through the entrance at Lysekil, while an almost equal quantity of water of the other layer is passing into the fjord. Thus an upheaval of the boundary is always accompanied by ingoing currents in the lower layers and by currents of seaward direction in the upper layer, a subsidence being characterized by movements of opposite direction. This transport of vast water-masses of more or less saline water exerts a profound influence over the pelagic fauna, including the fishes, since the currents may carry along with them mackerel shoals in summer and herring shoals in winter. (1)

Many of the larger "submarine waves" recorded at Bornö Station have occurred at intervals of about one or two weeks, and some of the very largest have culminated at or near full moon and new moon. This fact from the first led their discoverer to recognize them as parallactic tidal movements of the boundary, due to the long-period variations in the

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(1). Synoptical studies of the internal movements along the west coast of Sweden have proved the larger upheavals and subsidences of the boundary to take place simultaneously at different points on the coast. The boundary waves observed at Bornö thus form a part of general displacements of the different water-layers receding from or advancing towards the coast.

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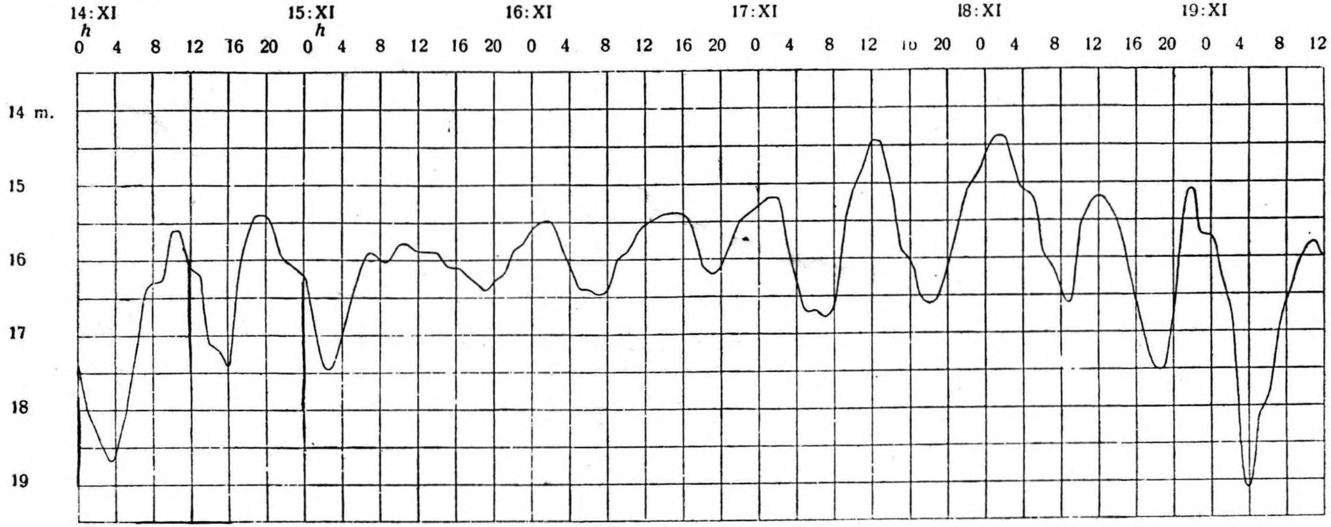

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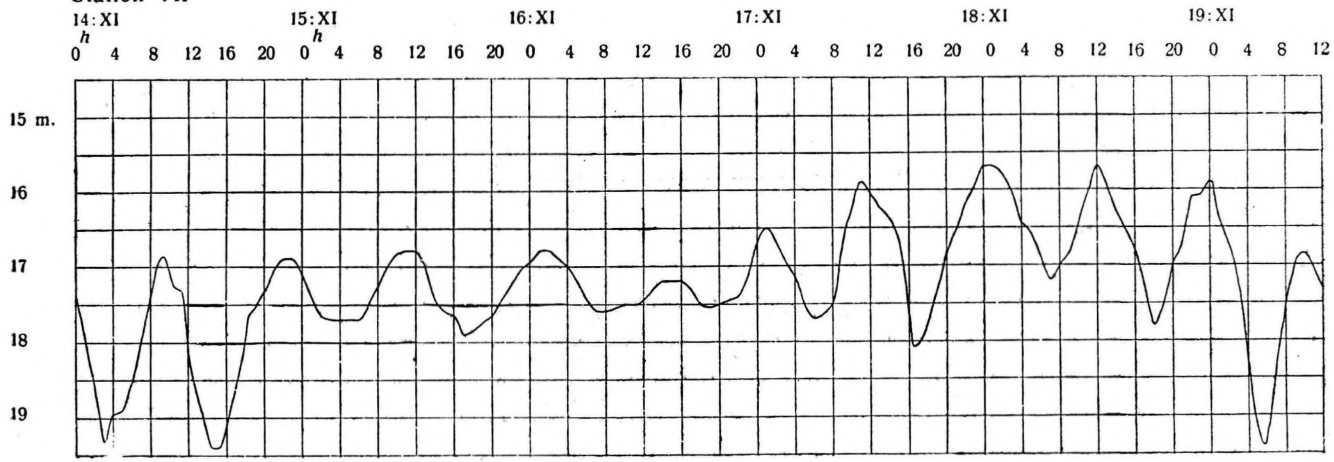

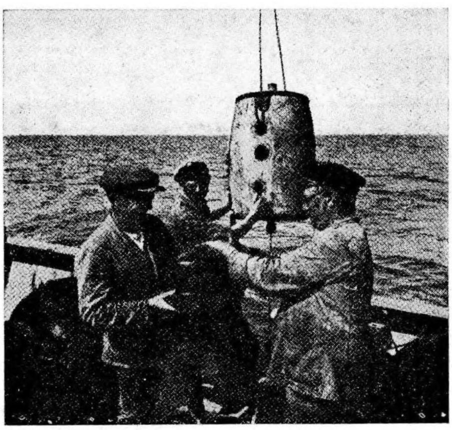

The Boundary Gauge.
Le Marégraphe frontière.

tide-generating force. This explanation has not, however, been generally accepted and, as a matter of fact, the winds playing over the fjord have been found to exert a considerable influence on the boundary movements. Thus a wind from the sea pushing the surface-layer landwards and increasing in thickness within the fjord, "Windstau", will indirectly act on the lower stratum also which, through an increase in the hydrostatic pressure becomes pressed seawards, thus lowering the level of the boundary between the layers by a multiple of the rise of the free surface. Still this explanation does not hold for some quite considerable upheavals of the boundary, which have occurred during a dead calm or when a vast sheet of ice excludes any direct effect of the wind.

The theoretical aspect of the problem is highly complex and the genesis of the internal waves has so far not been satisfactorily explained.

Nils Zeilon, who for a few years acted as Ist assistant at Bornö Station, made a very careful study of the seiches of the Gullmarfjord, the main period of which is 110 minutes. He found waves of the same period to occur also in the boundary, a phenomenon which he explained as due to the horizontal currents accompanying the surface seiche causing a kind of breakers in the boundary when passing an obstacle like the threshold of the fjord, situated near the boundary level. This explanation which was supported by very beautiful and convincing experiments he has also applied to the internal waves of tidal character discovered in the Belts and elsewhere. In a later paper Zeilon has shown how such free progressive waves in the boundary are generated, when periodically changing currents pass over a coastal bank, situated at approximately the same level as a boundary surface. Finally, even a strong current entering into stratified water from a river, or else a local current set up by a strong wind in the sea surface may act as a transformer, converting part of the energy of the tidal currents into boundary waves of the same period.

FURTHER EXPERIMENTAL WORK ON INTERNAL WAVES

Whereas observations of salinity and temperature once a day or even oftener are perfectly feasible from an observation pier like that at Bornö Station, similar sustained observations of the internal movements in the open sea are most laborious and expensive to carry out, say from anchored ships, and may have to be discontinued at the shortest notice owing to weather conditions becoming too rough. But even at Bornö observations of greater frequency than once in 24 hours involve a great amount of human labour, and for this purpose the construction of some recording contrivance becomes a necessity.

Already in 1909 Otto Pettersson had a large submarine float constructed, consisting of a copper cylinder holding some 500 litres and filled completely with water and oil. The weight of the metal was balanced by a counterpoise united with the float by a string running over a bicycle wheel mounted at the head of the observation pier. The whole system was carefully balanced, so that the copper float just swam in the boundary surface and rose and fell with the latter, being prevented from drifting away with the horizontal currents by means of two vertical guides along which small wheels mounted on the float were running. The movements of the bicycle wheel as the float rose or fell with the boundary movements were recorded on a papered drum turned by clockwork.

This contrivance was found to do excellent service under favourable conditions but was very easily deranged, floating sea-weed or jellyfish which became entangled in the guide-wires fouling the wheels. Also a very thin sheet of ice in winter made it necessary to dismount the float, or the wires and the recording string might easily have become cut.

After several futile attempts the rather formidable technical difficulties inherent in the construction of a similar " recording boundary gauge " for use in the open sea have finally been overcome, largely thanks to collaboration with Fil. lic. B. Kullenberg, Ist assistant to our "Kommission."

A commercial kerosene drum, holding about 200 litres, is provided with an axial tube of two inch bore, welded securely into the centre of the lid and of the bottom of the drum with both ends slightly protruding. Into these are inserted thick glass rings, in order to reduce friction against the single guide wire which is running straight through the tube. In order to make the drum sufficiently light it is partly filled with large glass bulbs, such as the herring-fishermen use for floats on their purse seines. The rest of the volume is filled air-free with tap water. The surplus buoyancy of the drum is counterbalanced by attaching to its lower rim a recording pressure gauge, hermetically sealed, and a counterpoise. The gauge writes a curve on a paper moved by clockwork giving the depth (in metres) in which the drum is floating. The disk makes one revolution in a week, but the clockwork when wound up keeps it moving for over three weeks.

The boundary gauge is mounted below a submarine buoy pulled down to, say 5 metres below the surface by means of two diverging anchorages, marked by separate surface buoys which carry flags and an electric torch burning for 2 weeks. Below the submarine buoy

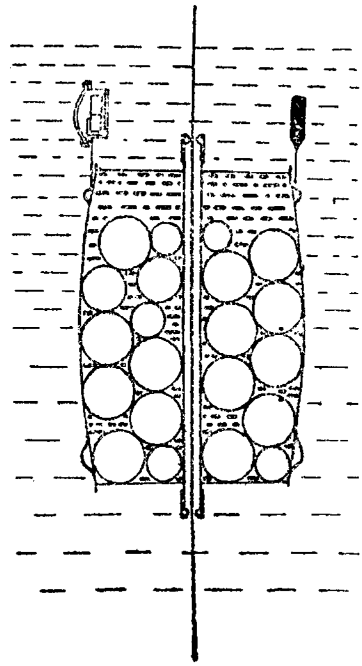

Fig. 1

the drum is free to rise and fall by 15 to 30 metres. It is prevented from becoming carried away by horizontal currents by means of the guide wire which runs through its axial tube and is stretched by a heavy weight.

The drum has to be balanced very carefully so as just to float in the boundary surface i. e. in the transition-layer, where the vertical density gradient has a maximum value. Special

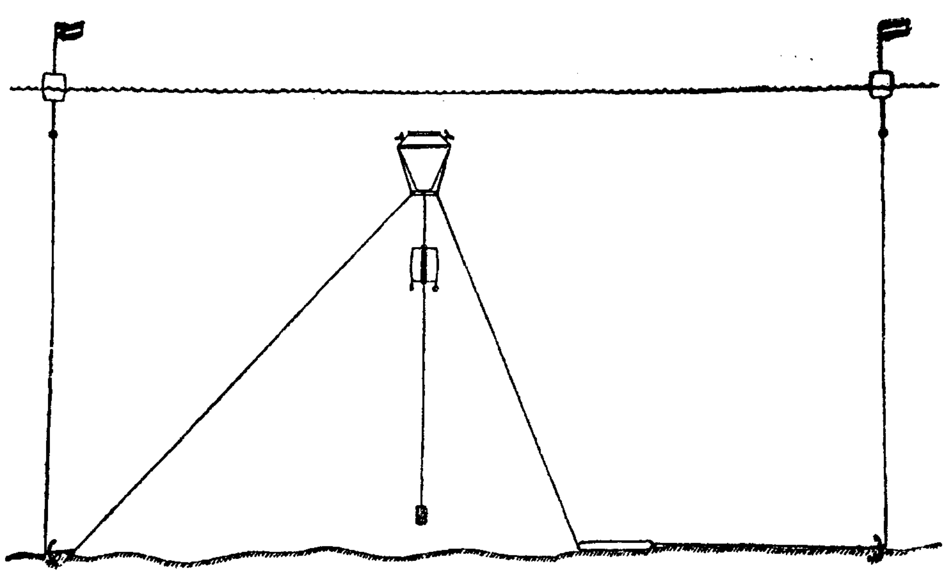

Fig. 2

tests have shown that the equilibrium of the float is disturbed already by a surplus weight of 20 grammes only, so that under favourable conditions it will react to changes in the density of the surrounding water of only 0.0001. Under actual working conditions this theoretical limit of sensibility is naturally never attained, since friction against the guide wire, however much reduced by the glass rings, will inevitably somewhat retard the movements of the float relative to the boundary. (2)

The boundary gauge here described, of which the "Kommission" thanks to the generosity of Knut and Alice Wallenbergs Endowment, have acquired three complete units, has repeatedly been put to practical tests in central Kattegat mainly round or near the Fladen Bank. latitude 57°10'N, longitude 11°45'E. The purpose in view was, first to obtain records of sufficient duration for a complete analysis of the semidiurnal lunar and solar tidal components, M_2 and S_2, secondly to find out whether the internal waves in the open sea are of the standing or of the progressive type, and thirdly, in case the latter should prove to be the case, to ascertain their direction of travel, their velocity and, if possible, their origin.

These different purposes have in fact largely been realized, thanks to the work of Kullenberg, who has published a preliminary report in "Meddelanden fran Göteborgs Högskolas Oceanografiska Institution" N° 3, 1932, and a more comprehensive treatise in "Svenska Hydrografisk-Biologiska Kommissionens Skrifter Ny Serie Hydrografi" Häfte XII, 1935. The main results from the latter paper will be summarized in the following.

From two unbroken records extending over nearly 15 days, November 6th to 21st 1932, a harmonic analysis has been carried out giving the amplitudes and phase-angles embodied in table I.

The amplitudes at the former station, which is closer to the bank, are seen to be distinctly greater than at the second station, the phase-angles for the lunar component M_2 are almost identical, the difference corresponding to a time lag of only 2 minutes whereas for the solar

Table I.

	Lat.: 57° 14',0 Long.: 11° 43',4		Lat.: 57° 16',6 Long.: 11° 40',6	
	amplitude	phase-angle	amplitude	phase-angle
M_2	66 cm.	68°	58 cm.	67°
M_4	10 »	315°	6 »	356°
S_2	32 »	79°	23 »	45°
S_4	7 »	104°	—	—

component S_2 the lag, which, owing to the smaller amplitude is correspondingly more difficult to determine with accuracy, is rather more than half an hour. This would imply that the boundary tidal waves, which had by preliminary measurements been proved to be of the progressive type, should travel approximately at right angles to the line between the two stations, or from N 60° E towards S 60° W. This result agreed with observations previously made with records of shorter length, proving that the origin of the tidal boundary waves must be the Swedish coast bank running at a distance of some 15 kilometres from the points of observation. From other records obtained from points of anchorage lying at different distances from the coast, so that a perceptible difference in the phase-angles of the semidiurnal lunar tide was apparent, the velocity of propagation could be calculated, the result being 0,89 m/sec. in good agreement with the theoretical value 0,93 m/sec. found from the simplified Greenhill formula :

$$V = \sqrt{g \cdot \frac{\delta_2 - \delta_1}{\delta_2} \cdot \frac{1}{\frac{1}{d_1} + \frac{1}{d_2}}}$$

where δ_1 and δ_2 are the densities of the upper and the lower layer, d_1 and d_2 being the thickness of the layers in metres.

(2) Thanks to the incessant rocking motion of the submarine carrier buoy, due to the surface waves, this tendency of the float to become retarded by friction is as a rule counteracted very efficiently.

A conspicuous feature of the records were pronounced variations in amplitude, characteristic of a "Schwebungskurve" with a beat period of about 4 days. This would imply that, beside the tidal components of semidiurnal period, there are also other periodic elements present in the boundary movements. By working out periodogrammes after Schuster's method from two of the best records Kullenberg found, beside the 12.4 hour period other maxima corresponding to the following periods, viz. 9.5, 11, 13.5, 14.5 and, although much less distinct, 20 hours. Of these components only those of 11, 13.5 and 14.5 hours' period may be considered as fairly well established, according to the usual criteria. It is interesting to observe that a periodic element in the currents of 14.5 hours period, or 12 "pendulum hours" at this latitude, has been discovered through continuous current measurements in the Baltic. Such "inertia currents", although masked by the tidal currents, are no doubt present also in the Kattegat and may be responsible for corresponding components in the boundary waves, generated according to Zeilon's theory. Regarding the other periodic elements found from the records, whether due to seiches of the water masses between the coasts of Denmark and of Sweden, or generated in some other way, nothing definite can be said at present, until further evidence for their existence has been produced.

It might be added that in the following year, 1933, when three boundary gauges had again been anchored off the west coast of Halland, a heavy gale broke out before they could be taken on board. Consequently the three anchored stations had to be left to the mercy of the waves and could not be salved until the gale had abated. Two of the gauges were recovered undamaged and their records showed very large displacements of the boundary had taken place during the gale. The third float had broken loose, but was recovered 6 months later, having been captured in the trawl of a Danish fishing vessel at some 100 kms distance to the SW from the point of anchorage, where it had drifted with the bottom current. Even the record was in order although hardly legible owing to the violent displacements to which the float had been subjected.

It should be observed here that, owing to the pressure against the guide wire due to horizontal currents, the boundary gauge is less sensitive to displacements of the boundary than the experiment before mentioned would imply. This is especially the case when the density gradient at the boundary is in itself not very strong. For this reason the displacements actually recorded are to be considered as affording minimum values of the boundary movements actually occurring. A reconstruction of the floats aiming at a reduction of the friction is at present being undertaken. Even in their present state, however, the boundary gauges afford facilities for observing the internal movements in the open sea with a completeness which it would be almost impossible to realize by personal observation from anchored ships.

General aspects of the internal movements

Apart from the great interest to dynamic oceanography inherent in the study of the internal movements, they have important bearings also on marine biology. To the biological aspects of the radical changes due to internal movements occurring in the course of a day or two within the fjords attention has already been called. But also the vertical displacements of a boundary surface per se must have direct consequences for the micro-organisms accumulating in the transition-layer.

Swedish measurements of the transparency of sea-water *in situ* have proved, that there is in general an accumulation of scattering particles, chiefly of organic matter, plankton and *detritus*, in or just below the boundary where the sinking motion of such particles is retarded, owing to the increase in density or in viscosity or in both, with depth. Hence these boundaries or transition-layers tend to become feeding grounds for zoö-plankton and also beds for the growing phyto-plankton, which will rise towards the surface or recede from it downwards, as the boundary rises and falls. These movements, therefore, will bring the phyto-plankton under varying conditions of illumination with daylight, which must profoundly influence their photosynthesis, especially during the spring increase of diatoms. Considering the vast importance of the latter process as regulating the productivity of the sea, not only immediately but for years to follow, a closer study of the internal movements especially during early spring seems to be warranted also from the biologists' viewpoint.

Further the exchange of water between the fjords and the sea, as well as between the Baltic and the Kattegat being largely regulated through the internal movements, not only the salinity and temperature of the enclosed bottom areas but also the oxygen content of the lowest water strata is largely dependent on the internal waves breaking over the thresholds and sending gusts of aerated water into the depths inside, in certain cases rescuing the bottom fauna from asphyxation or even from poisoning with sulphuretted hydrogen.

Finally both the formation and the breaking up of the ice over the fjords in winter is profoundly influenced by the stratification of the water. A thin surface layer of brackish water, prevented by its low density from mixing with the salt water below, however strongly cooled at the surface, will freeze very rapidly and form thick ice obstructing the traffic, although water of + 7° or even more may be present less than one metre below the ice sheet. On the other hand a strong surface current carrying warm and salt water in from the sea may clear large areas from ice in the course of a single day or even in a few hours, although the air temperature may remain below freezing point the whole time.

It is, therefore, hardly an overstatement to characterize the internal movements, whether of wave-character or aperiodic in nature, as one of the most important phenomena going on in coastal waters, well deserving of increased study both from oceanographers and biologists.

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