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PHYTOPLANKTON PRIMARY PRODUCTION IN SOME FINNISH COASTAL AREAS IN RELATION TO POLLUTION

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Measurements of phytoplankton primary production, made mainly by the *in situ* carbon-14 method, have been carried out by various workers in several unpolluted and polluted coastal areas of Finland during the last six years. The intensity and dynamics of primary production in unpolluted areas were observed to differ in several essentials from those of areas receiving effluents from settlements and industries. Differences were found, among others, in the following parameters: intensity of annual primary production, intensity of daily production in summer, time of maximum production, algal groups responsible for maximum production, and the intensity of dark fixation.

Measurements of phytoplankton primary production have been made in several Finnish coastal areas during the last six years mainly by the *in situ* carbon-14 method (*cf.* Steemann Nielsen, 1952). Measurements have been carried out by the Institute of Marine Research, the Department of Limnology of the University of Helsinki, the Water Conservation Laboratory of the City of Helsinki, the Fisheries Foundation, and the Associations for Water Pollution Control of South-western Finland and Kymijoki. Some of the data collected have already been published by Lehmusluoto (1967a, 1967b, 1968 and 1969), Jumppanen (1969) and Bagge & Niemi (1971).

The discussion presented in this paper is mainly based on the data above, though some additional unpublished results obtained by the Institute of Marine Research during the years 1967—69 have also been used. The aim of the study was to determine the intensity and fluctuations of phytoplankton primary production and to discover possible differences in the dynamics of production between unpolluted and polluted habitats.

METHODS

Phytoplankton primary production was measured mainly *in situ* according to Steemann Nielsen (1952) and UNESCO (1967). Water samples were collected from selected depths with a Ruttner sampler. They were dispensed into 100—120 ml transparent glass bottles. $NaH^{14}CO_3$ ampoules, having a specific activity of 1 microcurie, were used. Light and dark bottles were suspended at selected depths. After 24 hours, which has been suggested to be the best incubation time for ecological studies (Westlake, 1965), the photosynthesis in the bottles was stopped by adding 1 ml concentrated formalin. The whole contents of the bottles were filtered on membrane filters (Sartorius 11406, pore size 0.45 μ) and the radioactivity of the residues on the filters was measured with an end window counter.

In some study areas the samples were incubated at constant light and temperature (4 000 lux, 19°C) for 18 hours (*cf.* Lehmusluoto, 1968).

Quantitative analyses of phytoplankton were made in some study areas in connection with the production measurements. Since not all the results of the plankton counts are available yet, only scattered remarks on phytoplankton biomass will be made in this paper.

The total CO_2 values for the calculation of the primary production were obtained from the formula and diagrams of Buch (1945).

The assimilation values are expressed as g C/m³ or g C/m² per day or as g C/m²/year. The dark fixation values have been subtracted from the light values and, as the incubation time was 24 hours, the figures show the approximate net primary production (*cf.* Fogg, 1969).

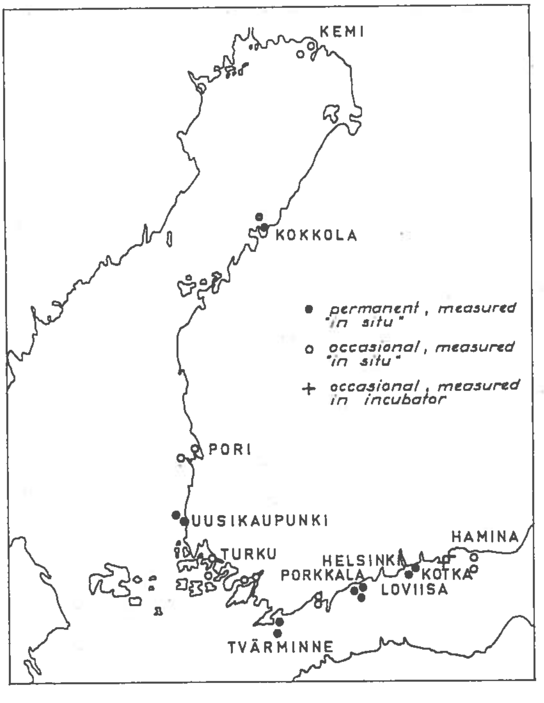

Fig. 1. Sampling localities along the Finnish coast

THE STUDY AREAS

Measurements of phytoplankton primary production were made in several coastal areas (Fig. 1). The main study areas were Kotka, Loviisa and Helsinki in the Gulf of Finland, Uusikaupunki in the Bothnian Sea and Kokkola in the Bothnian Bay.

All of the sampling localities are situated in the archipelago zone or in bays and are relatively shallow (2—45 m). The sea areas around Kotka and Pori have a clear estuarine character with a rapid exchange of water and fluctuating salinities. The Loviisa area, being partly isolated from the open sea by shallow sills, has rather stagnant conditions in deep water during a great part of the year (Bagge & Voipio, 1967).

The areas compared represent different salinity ranges; their conditions varying from oligohaline to β-mesohaline (*cf.* Venice system, 1958). The sea areas around Uusikaupunki and Helsinki are β-mesohaline, while the other areas are partly or totally oligohaline.

The ice-free period lasts about 8—9 months on the southern and southwestern coast of Finland, 7—7.5 months in Kokkola and only 6.5 months in Kemi (Palosuo, 1965). The values of total incoming solar radiation measured in the northern parts of the Bothnian Bay during the period of growth are on an average *ca.* 10 per cent smaller than those obtained on the southern coast of Finland (Lunelund, 1948).

In several study areas a clear pollution gradient was observed. The areas can be grouped according to the type and source of waste waters as follows:

1. Areas receiving no apparent waste waters (*e.g.*, Hamina, Loviisa and Tvärminne) and the outermost sampling localities off Helsinki, Porkkala and Uusikaupunki.
2. Areas receiving large amounts of domestic sewage or other nutrient-rich wastes, *e.g.*, innermost bays of Helsinki, Pori and Uusikaupunki.
3. Areas mainly contaminated by waste waters from chemical (mainly inorganic) and metal industries (Kokkola and the outermost sampling locality off Pori).
4. Areas receiving both domestic sewage and pulp mill wastes (Kotka and Kemi).

The actual concentration of waste waters in the samples was not determined. Some data of the total load of nutrients or other substances introduced into the study areas are given with the results.

RESULTS

Primary production values (g C/m^2 per day and per year) obtained *in situ* at 6 sampling localities off Helsinki during the growing period 1967 are presented in Fig. 2. The production values are according to Lehmusluoto (1968) and the data of mean solar radiation (kcal/m^2/min at 60°N) according to Smayda (1959). The two innermost localities are heavily polluted by domestic sewage, while the outermost localities represent fairly unpolluted conditions. According to Karimo *et al.* (1970) the waste waters discharged annually in the innermost bays of Helsinki have a BOD$_5$ load

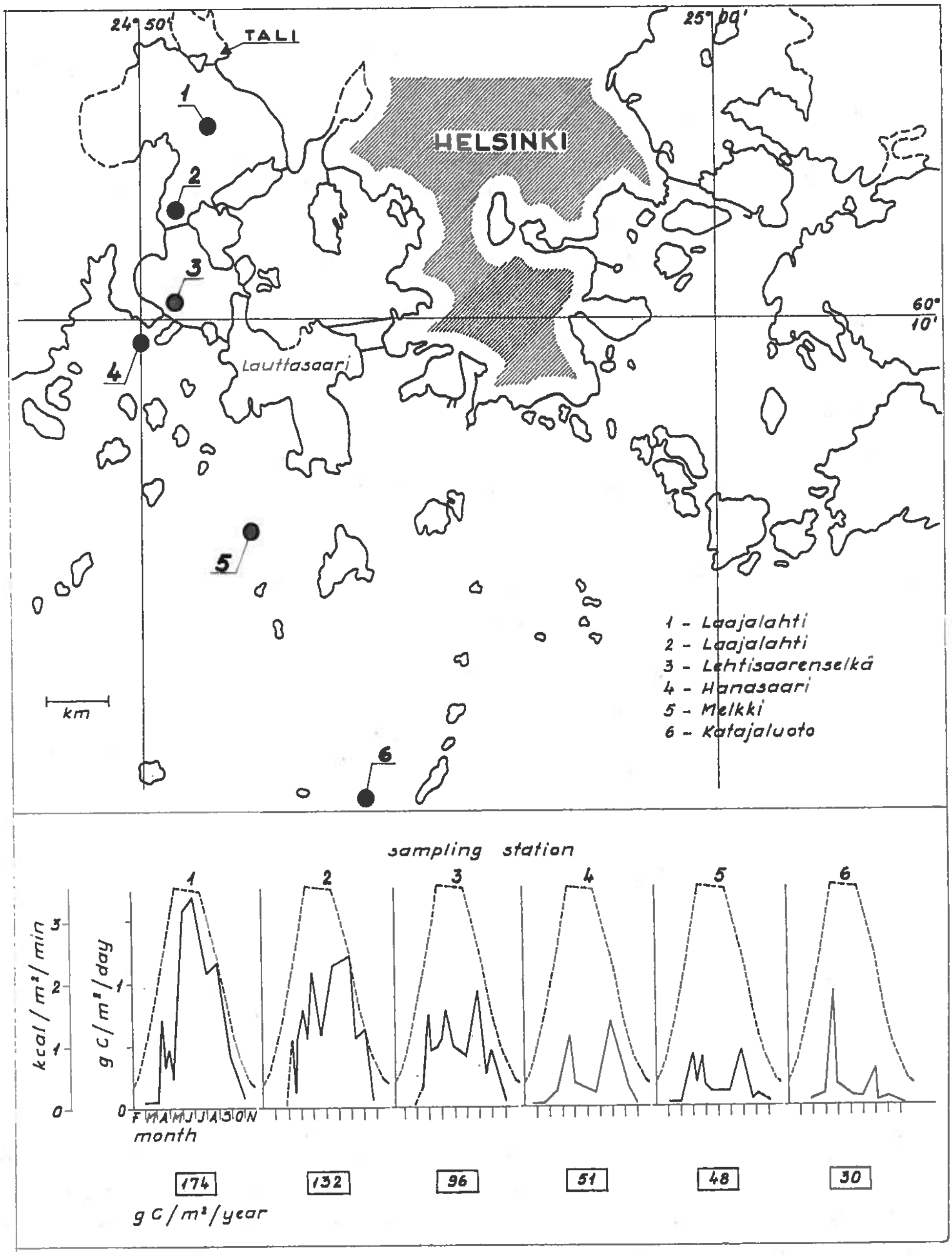

Fig. 2. Sampling localities off Helsinki and primary production as g C/m²/day during the growing season of 1967 (solid line), and as g C/m²/year (fiqures in squares). The dotted line respresents the mean solar radiation at 60° N as kcal/m²/min. Domestic sewage is discharged into the bays west of Helsinki mainly in Tali.

of *ca.* 16 000 tons and total nitrogen and phosphorus loads of *ca.* 3 000 and 650 tons, respectively.

The dynamics of the primary production seems to be different at different localities. The maximum primary production in the innermost bays was observed in June—August, when the blue-green algae were abundant. The depth of the trophogenic layer was at that time less than 2 metres in the innermost localities. In the Katajaluoto area (Station 6) primary production was most intensive during the vernal bloom of diatoms in May and very low in July. The depth of the trophogenic layer at this locality was usually more than 10 metres. The layer becomes shallower towards autumn. During November—March the primary production values were very small; especially low values were measured under snow-covered ice (Lehmusluoto, 1968).

Annual production values (Fig. 2) decrease sharply from the innermost bays of Helsinki towards the open sea. The annual values during the period 1966—69 at some localities off Helsinki are presented in Table 1.

TABLE 1. *In situ* primary production g C/m²/year during the period 1966—69 at some localities off Helsinki (Lehmusluoto & Pesonen, unpubl.).

Locality (See Fig. 2)	1966	1967	1968	1969
	g C/m²/year			
1. Laajalahti	120	174	192	(80)
3. Lehtisaarenselkä	95	96	122	(69)
4. Hanasaari	36	51	42	66
5. Melkki	21	48	37	41
6. Katajaluoto	15	30	28	36

As indicated in Table 1, the production values fluctuate considerably from year to year. Especially high values were observed at the innermost localities during the years 1967 and 1968 and low values in 1969. In the outermost part of the study area the production was low in 1966 and higher in 1969.

Some *in situ* measurements of primary production in the sea area off Uusikaupunki in July 1967 are presented in Fig. 3 (*cf.* Lehmusluoto, 1967a). The area receives waste waters from the town and from a factory producing fertilizers. According to Karimo *et al.* (1970), the annual load of wastes in the innermost bays of Uusikaupunki amounts to circa 20 000 human population units in respect to total phosphorus, and to *ca.* 10 000 units in respect to total nitrogen. As seen in Fig. 3, the production values were highest near the town and the factories (*ca.* 1.2 g C/m²/day) and decreased sharply towards the open sea, being 0.16 g C/m²/day at Stat. XII.

Some values of primary production based upon measurements made at two localities in the Loviisa archipelago during the period April 1967 — October 1969 have been published by Bagge & Niemi (1971). The study area can be considered to be rather unaffected by pollutants, although small amounts of sewage from the town Lovisa/Loviisa may occasionally spread to station 2 (*cf.* Table 3). The daily production values in the area were about 0.4 g C/m² in May, 0.1—0.2 g C/m² in June

—September and only 0.015—0.075 g C/m^2 in October—November. The depth of the trophogenic layer was usually more than 10 metres in summer and decreased towards autumn. The annual primary production values in the area were estimated by Bagge & Niemi (1971) as follows: *ca.* 30 g C/m^2 in 1967, *ca.* 32 g C/m^2 in 1968 and *ca.* 40 g C/m^2 in 1969. About one third of the annual yield was estimated to be produced during the vernal bloom of diatoms and *Dinophyceae* in May.

The dark fixation of the samples was small, ranging from 1.8 to 14.1 cpm (counts/minute), being 1.9 to 11.1 % of the light values in the layer of maximum production during the ice-free period. Under the ice-cover the corresponding percentage values ranged from 52 to 72 %.

Some *in situ* measurements of primary production made during the years 1967 and 1968 in Ykspihlaja Bay (Kokkola Fig. 4) are presented in Table 2. The area receives waste waters from chemical and metal factories. The effluents contain pH-reducing substances (sulphuric acid) and some heavy metals, mainly in the form of insoluble solids.

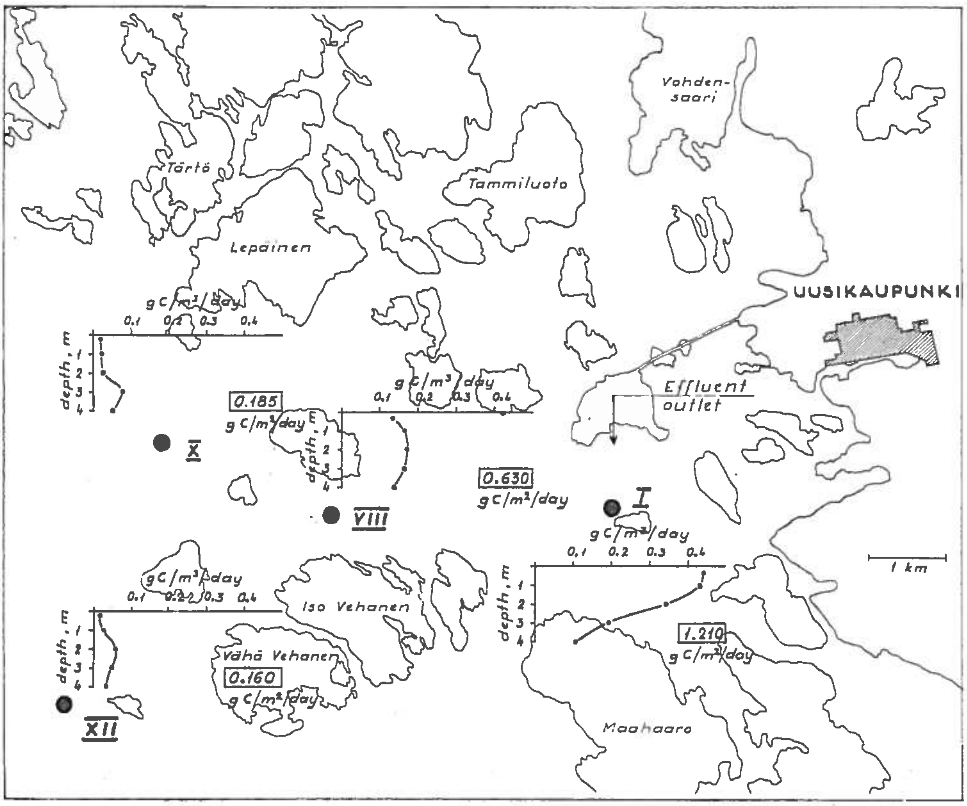

Fig. 3. Sampling localities off Uusikaupunki and the primary production as g C/m^2/day (vertical lines) and as g C/m^3/day (figures in squares) in July 1967.

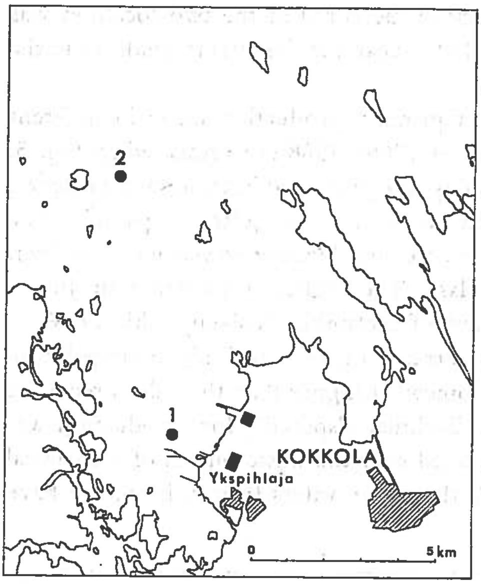

Fig. 4. Sampling localities in Ykspihlaja Bay. Black squares east of Station 1 show the location of industries.

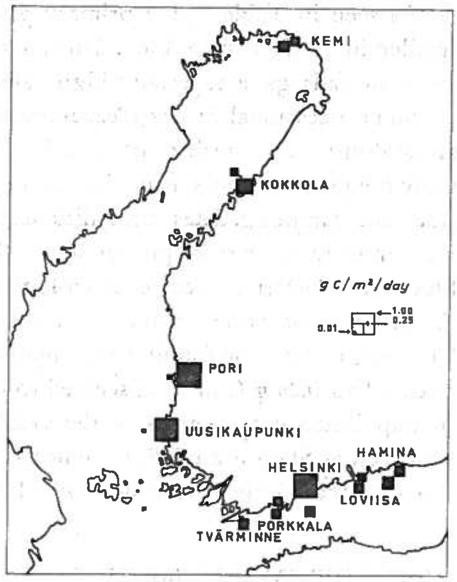

Fig. 5. Daily *in situ* primary production in some sampling localities along the Finnish coast in July—August 1966—68.

TABLE 2. Daily *in situ* primary production values at different depths in Ykspihlaja Bay during the years 1967 and 1968. For localities see Fig. 4.

Depth m		g C/m³/day						
		1967				1968		
		June 17	July 12	Aug. 22	Sept. 14	June 27	July 29	Sept. 3
0.5	St. 1	0.100	0.049	0.054	0.026	0.097	0.175	0.108
	St. 2	0.145	—	0.031	0.029	0.045	0.021	0.110
1.5	St. 1	—	—	—	—	0.098	0.135	0.090
	St. 2	—	—	—	—	0.040	0.021	—
3.0	St. 1	0.049	0.030	0.002	0.013	0.046	0.048	0.046
	St. 2	0.084	—	0.017	0.019	0.032	0.018	0.091
5.0	St. 1	0.017	0.008	0.000	0.003	0.011	0.007	0.019
	St. 2	0.040	—	0.001	0.008	0.008	0.009	0.005
7.5	St. 1	0.002	0.003	0.000	0.002	0.002	0.002	0.004
	St. 2	0.009	—	0.001	0.002	0.001	0.001	0.000
10.0	St. 1	0.002	0.000	0.000	0.001	—	—	—
	St. 2	0.001	—	0.001	0.002	0.001	0.001	0.000
g C/m²	St. 1	0.329	0.176	0.088	0.087	0.334	0.461	0.351
	St. 2	0.559	—	0.098	0.120	0.172	0.106	0.301

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As seen in Table 2, the primary production measured at the two localities was smaller in 1967 than in 1968. During the latter year measurements made near the waste outfalls gave especially high values.

Some occasional *in situ* measurements of primary production made in different areas along the Finnish coast in July—August 1966—1968 are presented in Fig. 5. Only the measurements made during bright days are presented in the figure; however, since the sampling dates were different, the results are not quite comparable. The measurement of primary production in the sea area off Tvärminne was made by Prof. Steemann Nielsen's productionbiological class. The highest production in July—August was observed in the innermost bays of Helsinki, Uusikaupunki and Pori. The daily production found in the unpolluted areas in the Gulf of Finland ranged from circa 0.1 to 0.28 g C/m² and seemed to be somewhat higher than the values recorded in unpolluted coastal areas of the Gulf of Bothnia. Especially low production was observed at Station 2 off Pori, which is situated near the waste outfall of a chemical factory. According to Karimo *et al.* (1970), the waste waters from this factory have

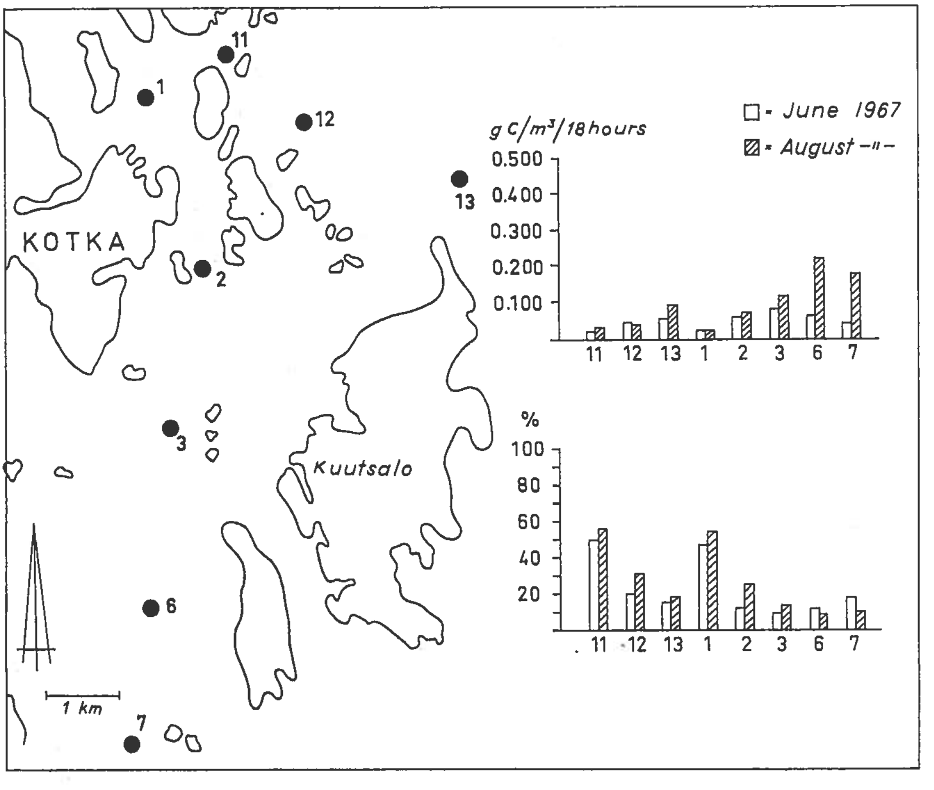

Fig. 6. Primary production (g C/m²/18 h.) and dark fixation, as percentages of the light values, of surface water samples collected in some localities in the sea area around Kotka in June and August 1967. The samples were incubated at 19° C and 4 000 lux.

annual loads of 100 000 tons H_2SO_4, 50 000 tons ferrosulphate and 3 000 tons titan-oxide.

The results of some *in situ* measurements in light and dark made in July—August 1967 in several study areas are presented in Table 3. The first depth given for each locality represents the depth where maximum production was observed. As seen in Table 3, the dark fixation values were highest in areas receiving domestic sewage (*e.g.*, Helsinki and Pori), but represented only a small percentage of the light values. High dark fixation values were also obtained near a sugar mill (Porkkala, Station 1).

Some values of the primary production (measured in an incubator) of water samples collected in the sea area around Kotka are presented in Fig. 6 (*cf.* Lehmusluoto, 1967b). According to Karimo *et al.* (1970), the sea area off Kotka receives large amounts of waste waters via the River Kymijoki and from coastal settlements. The

TABLE 3. Light and dark fixation values (cpm) of samples *(in situ)* collected in different study areas in summer 1967

Area	Station	Date	Depth/m	*light* cpm	*dark* cpm	dark as % of light
Hamina	1	22/7	3	146.5	11.8	8.0
Hamina	1	22/7	5	120.6	9.1	7.5
Hamina	2	22/7	3	206.5	5.7	3.0
Hamina	2	22/7	5	135.7	7.9	5.8
Loviisa	1	8/7	0.5	134.1	7.3	5.4
Loviisa	1	8/7	5	59.1	3.8	6.4
Loviisa	2	8/7	0.5	162.9	6.6	4.0
Loviisa	2	8/7	5	66.4	4.6	6.9
Helsinki*	1	18/7	0.1	4 976.0	150.0	3.0
Helsinki	1	18/7	2.0	258.0	200.0	77.5
Helsinki*	6	18/7	0.1	110.0	10.0	9.1
Helsinki	6	18/7	5	75.0	10.0	13.3
Porkkala	1	24/7	3.0	95.9	25.2	26.2
Porkkala	1	24/7	5.0	50.1	10.8	21.5
Porkkala	2	24/7	0.5	142.1	8.2	5.8
Porkkala	2	24/7	5	42.9	8.2	19.1
Pori	1	30/7	0.5	3 109.0	84.2	2.7
Pori	1	30/7	5.0	26.0	24.8	95.3
Pori	2	30/7	0.5	24.0	3.7	15.4
Pori	2	30/7	5.0	18.0	5.9	32.7
Kokkola	1	22/8	0.5	248.9	23.0	8.4
Kokkola	1	22/8	5	22.0	13.6	61.8
Kokkola	2	22/8	0.5	140.4	6.4	4.3
Kokkola	2	22/8	5	5.9	6.9	100

* Lehmusluoto & Pesonen (unpubl.)

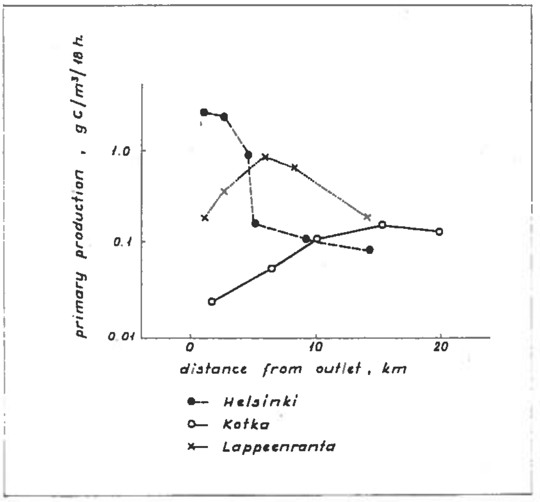

Fig. 7. Primary production values of surface water samples collected at different distances from effluent outfalls in the sea areas around Helsinki and Kotka and in the southern part of Lake Saimaa. The two last-named areas receive waste water from pulp mills, while in Helsinki the effluent consists mainly of domestic sewage. The samples were incubated at 19° C and 4000 lux for 18 hours.

BOD_5 of the wastes entering the area is estimated at 53 000 tons, the total nitrogen at 5 100 tons and the total phosphorus at 400 tons per year. The effluents contain both domestic sewage and pulp mill wastes. The concentration of the waste liquor from pulp mills is highest near the river mouth and decreases seawards. As seen in Fig. 6, the production of samples collected near the river mouth is low and the dark fixation values high compared with the same parameters in samples taken from the outermost localities.

Measurements made in an incubator of the primary production of some water samples collected at different distances from waste outfalls in Helsinki and Kotka are presented in Fig. 7. For comparison, a third curve is presented in the figure illustrating measurements made in the southern part of Lake Saimaa, which receives waste waters from pulp mills (*cf.* Lehmusluoto, 1969, Lehmusluoto & Heinonen 1970). In Helsinki the production in samples collected near the outfalls is about ten times as high as in samples from the outermost areas. In both the other areas the production of samples is low near the outfalls and increases outwards.

DISCUSSION

PRIMARY PRODUCTION IN UNPOLLUTED COASTAL WATERS

The *in situ* phytoplankton primary production in unpolluted coastal waters of the Gulf of Finland was discussed by Bagge & Niemi (1971). They compared the results of their production measurements made in two rather isolated sea areas of the Loviisa archipelago with similar records made by Lehmusluoto (1968) off Helsinki and with records of Buch (1948 and 1954) from Hanko and Utö. The annual primary production in all the areas compared ranged from circa 15 to 60 g C/m². One third of this amount was estimated to be produced during the spring bloom of diatoms and *Dinophyceae* in April—May, when daily production was found to be circa 0.4—0.9 g C/m². In summer the daily production values were usually 0.070—0.280 g C/m² (*cf.* Fig. 5) and in October—November only 0.015—0.075 g C/m². The phytoplankton biomasses were greatest during the spring maximum of diatoms (*ca.* 12—40 mg/l) and very low in summer (0.1—2.0 mg/1).

Other features typical of the production processes in unpolluted waters are as follows:

1. The trophogenic layer is at least 10 m thick in summer. The layer gets thinner with decreasing illumination in autumn.
2. The primary production values and the phytoplankton biomasses are small in summer but the renewal coefficient (*cf.* Kristiansen & Mathiesen, 1964) calculated as the ratio of primary production to total phytoplankton biomass is high (Bagge & Niemi, 1971).
3. Dark fixation in the layer of maximum production is low (*cf.* Table 3) being usually less than 5 per cent of the light values.
4. The annual production values seem to fluctuate moderately from year to year. The annual *in situ* primary production in the two sampling areas off Loviisa and in the Katajaluoto area is presented in the following tabulation, the production values being expressed as g C/m²/year.

	1966	1967	1968	1969
Loviisa Station 1	—	29.7	30.8	35.4
Loviisa Station 2	—	33.1	35.3	43.0
Helsinki Katajaluoto (Lehmusluoto & Pesonen, unpubl.)	15.0	30.0	28.0	36.0

As seen above, the production values are rather similar during the years 1967 and 1968 in all the areas compared, but in 1969 they were considerably higher. As was mentioned by Bagge & Niemi (1971), the increased production of the waters of the Loviisa area in 1969 seemed to be connected with favourable climatic conditions and numerous influxes of saline subsurface water from areas outside the archipelago.

Measurements of the phytoplankton primary production in the unpolluted areas of the Gulf of Bothnia are too few to allow exact estimates of the intensity of the annual production. Some summer measurements made in areas of Uusikaupunki (Lehmusluoto, 1967b, Jumppanen, 1969), however, indicate that the annual production in the Gulf of Bothnia is lower than that of the Gulf of Finland. This conclusion is supported by differences between these waters in some factors vitally affecting production:

— the ice-free period lasts about 2 months longer off the southern coast of Finland than in the Bothnian Bay, thus the period of growth is longer in the former area,

— the concentration of nutrients, especially of total phosphorus (Voipio & Särkkä, 1969) is higher in the Gulf of Finland than in the Gulf of Bothnia. The northern coast of the Gulf of Finland lies in the upwelling zone, where nutrient-rich water from the deeper layers rises into the trophogenic layer. In the Gulf of Bothnia such upwelling seems to be more occasional and, since the deep water there is poor in nutrients, it should not favour production to as great degree as in the Gulf of Finland.

PRIMARY PRODUCTION IN COASTAL WATERS RECEIVING NUTRIENT-RICH EFFLUENTS

As was shown in Figs. 2 and 3 and in Table 1, nutrient-rich effluents discharged into the sea cause a remarkable increase in both daily and annual primary production values near their outfalls. Moreover it was shown that the production decreases with increasing distance from the sewers. Lehmusluoto (1968) divided the sea area off Helsinki into four zones, according to the intensity of the *in situ* primary production.

In the heavily eutrophic zone annual production is more than 120 g C/m^2, in the eutrophic zone 80—120 g C/m^2, in the slightly eutrophic zone 40—80 g C/m^2 and in the oligotrophic zone less than 40 g C/m^2/year. The degree of eutrophication and the area of the zones in the sea region off Helsinki seem to vary from year to year (*cf.* Table 1). Thus no definite limits can be given for the zones. As seen in Table 1, primary production was low in the innermost bays of Helsinki in 1969 while at the same time an increase in production was observed in the outermost localities of the area. The reasons for the remarkable fluctuations of the annual production values in the eutrophic bays of Helsinki are not known in details, but they can be supposed at least partly to be due to hydrographic conditions. An analysis of the effects of hydrographic factors on the primary production will be published in the near future by the Water Conservation Laboratory of the City of Helsinki.

A reasonable correlation between the load of nutrients and the area of the heavily eutrophic zone is revealed when the innermost bays of Helsinki and Uusikaupunki are compared (Table 4).

As is shown in Fig. 2, the dynamics of the phytoplankton primary production in the eutrophic bays of Helsinki differs in several essentials from that found in

TABLE 4. Load of nutrients (tons/year) and the width of the heavily eutrophic area in Helsinki (Lehmusluoto, 1968) and in Uusikaupunki (Jumppanen, 1969)

	total load, P/tons	total load, N/tons	heavily eutrophic area/km²
Helsinki	3 000	650	circa 40
Uusikaupunki	183	55	circa 1

the oligotrophic Katajaluoto area. The differences between the areas can be grouped as follows (*cf.* Lehmusluoto, 1968):

1. In the bays the maximum production is caused by blue-green algae, while in the Katajaluoto area the main part of the annual organic matter is produced during the spring bloom of diatoms.

2. The maximum production in the bays is observed in June—August, when a clear summer minimum is seen in the Katajaluoto area.

3. The main part of the production in the Katajaluoto area is observed at depths of 1—5 m, in the bays at 0—1 m.

4. The total depth of the trophogenic layer in the Katajaluoto area is usually more than 10 m, while the coresponding depth in the bays is usually less than 2 m owing to the self-shading effect of dense phytoplankton.

The results obtained when measuring primary production in waters off Helsinki show that in order to determine the trophic stage of a coastal area, measurements of production should be made during several periods of growth. As is seen in Fig. 5, measurements of production made in July—August may also help in determining the location and extent of eutrophic areas. During that period such areas are easily discovered owing to their high daily primary production.

PRODUCTION IN AREAS RECEIVING EFFLUENTS FROM WOOD-PROCESSING, METAL AND CHEMICAL INDUSTRIES

As is shown in Figs. 6 and 7, the primary production values of samples collected near the waste outfalls of pulp mills and treated in an incubator were much lower than those of samples collected at a greater distance from the outfalls (*cf.* Lehmusluoto, 1969). Since the samples were incubated at constant light intensity, the light-quenching effect of the sulphite waste liquor may not be responsible for the low production values obtained.

The concentration of nutrients in the pulp mill wastes is also relatively high (*cf.* ICES report, 1970). Thus the most probable reason for the low production values obtained in the areas concerned is some kind of toxic effect of the waste liquor on phytoplankton.

Järnefelt (1961) found clear qualitative and quantitative differences in the composition of phytoplankton between areas receiving and not receiving sulphite pulp liquor in the southern part of Lake Saimaa (*cf.* Fig. 7). Typical species in areas heavily polluted by sulphite waste liquor were different bacteria and some *Dinobryon* and *Dictyosphaerium* species.

As seen in Figs. 6 and 7, the effluents from pulp mills are able to cause slight eutrophication in the receiving waters at some distance from the outfalls, where the waste liquids are diluted and oxidized enough to be harmless to the producers.

Our measurements of primary production in areas receiving waste water from chemical and metal factories are too few to allow definite conclusions. In Ykspihlaja Bay (Kokkola) slight eutrophication was observed at Station 1, which is situated *ca.* 1.5 km west of the waste outfalls. On one occasion (August 22, 1967 *cf.* Table 2) the production values were abnormally low in the bay at depths below 3 m, which indicates some kind of inhibition. Some inhibition was also observed near the outfall of waste waters from a chemical factory in the Pori area on July 30, 1967. The counts of total bacteria made by the Water Protection Bureau (Mirja Särkkä, pers. comm.) in connection with the production measurements in this locality also gave abnormally low values.

SUMMARY

The *in situ* phytoplankton primary production in some polluted and unpolluted coastal areas of Finland shows remarkable seasonal and annual fluctuations, which at least partly seem to be connected with some climatic and hydrographic factors. The longer period of growth, the more frequent upwelling of deeper waters into the trophogenic layer and the higher content of nutrients, especially of phosphorus, in the coastal waters of the Gulf of Finland makes this area more productive than the coastal areas of the Gulf of Bothnia.

The intensity and dynamics of primary production in unpolluted coastal areas differ from those in areas receiving effluents from settlements and industries in several essential factors, as follows:

1. The annual primary production may locally exceed 150 g C/m^2 in areas receiving large amounts of domestic sewage and other nutrient-rich wastes. In unpolluted areas of the Gulf of Finland the annual production values range from circa 15 to 60 g C/m^2.

2. The maximum daily primary production in heavily eutrophic areas is observed in June—August, when daily values of circa 1.0—1.2 g C/m^2 have been recorded in several areas. In oligotrophic waters the maximum is found in May when about one third of the annual organic matter is produced. The daily production values in oligotrophic areas range from 0.070 to 0.280 g C/m^2 in the Gulf of Finland in summer, and seem to be still lower in the Gulf of Bothnia.

3. The main part of the organic matter in the eutrophic waters is produced in the surface layer (0—1 m) and the total depth of the trophogenic layer is usually

less than 2 m in summer, owing to the self-shading effect of dense phytoplankton. In areas polluted by pulp-mill wastes the trophogenic layer is also very shallow. In unpolluted areas the depth of the layer ranges from 7 to 15 m during the summer, and the main part of the organic matter is produced at depths of 1—5 m.

4. The most abundant planktonic algae during the period of maximum production in eutrophic waters are blue-green algae, while in the oligotrophic areas the diatoms and *Dinophyceae* are responsible for the main part of production.

5. In some areas receiving waste waters from pulp mills and chemical and metal factories the production near the effluent outfalls is sometimes unusually low, probably owing to light-quenching and toxic effects of the wastes. At longer distances from the outfalls the nutrients contributed by pulp-mill wastes may cause slight eutrophication.

6. Dark fixation values are high in eutrophic waters and in areas receiving wastes from pulp and sugar mills. In unpolluted areas the dark fixation values are circa 1/5—1/10 of those found in eutrophic areas.

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FURTHER DATA ON SUMMER-BREEDING IN BALTIC POPULATIONS OF THE AMPHIPODS *PONTOPOREIA AFFINIS* AND *P. FEMORATA*, WITH COMMENTS ON THE TIMING BROBLEM INVOLVED

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In a paper of 1967, the author demonstrated that in Baltic populations of the amphipods *P. affinis* Lindström and *P. femorata* Köyer, which normally breed in winter, the former species reproduces even in the warm season at depths below 100 m and that in the latter summer-breeding, which had earlier been observed below 85 m, may occur even at *c.* 60 m. Examination of new material of the two species collected off the south coast of Finland confirms the conclusions that breeding during the warm season is confined to deep water and that the minimum depth for such reproduction lies higher in *femorata* (at one station breeding found even at 45 m). For *affinis* even the deepest locality from which new material of this species was available (situated at 60 m) showed no indications of summer-breeding. The fact that, in both species, reproduction in this season is restricted to deep water and the differences between them in this respect are suggested to be due to the light factor.

In a recent publication (Segerstråle 1967) I have discussed the incidence of reproduction in *Pontoporeia affinis* Lindström and *P. femorata* Kröyer in Baltic waters, where these amphipods are among the main constituents of the benthic fauna. For the former species, the earlier view that in this area breeding is confined to the cold season (egg-laying in late autumn, release of the young from the brood-pouch of the mother in spring; *cf.* Segerstråle 1937) was shown not to cover the whole truth: in a number of samples collected below the 100 m level in the Gulf of Bothnia in the first half of June, 1965, not only spent females but also females with swollen ovaries or freshly deposited eggs in the brood-pouch were found. In the case of *P. femorata*, breeding in the Baltic area at other seasons besides the winter — the normal time of reproduction in this species — had already been reported earlier (Segerstråle 1938).

In this this case, too, such observations referred to deep water, *viz.* below the 85 m level. In my 1967 paper, the minimum depth at which summer-breeding was observed could be raised to about 60 m on the basis of samples collected in the Gulf of Finland in May, 1965 (presence of females with freshly deposited eggs).

THE NEW OBSERVATIONS

In order to obtain more information about the occurrence of summer-breeding in Baltic populations of the two amphipods under discussion, I collected additional material in the years 1967—1969 in the area adjacent to the Zoological Station at Tvärminne, situated on the southwest coast of Finland.[1]) Besides this material, which comprises 14 samples, I have had the opportunity to examine 8 further collections, kindly placed at my disposal by the following colleagues: Mr. Henrik Backman, Mr. Julius Lassig, Lic.Phil., and Mr. Ilkka Luotamo, Cand.Nat. These collections originate partly from the Tvärminne region, partly from areas further east in the Gulf of Finland, *viz.* open waters off the towns of Helsinki and Lovisa. All the material examined was collected by dredging. The depths sampled ranged from 44 to 73 m. The collecting period covered the time from late April to mid-August.

Pontoporeia affinis. Females with freshly deposited eggs were totally lacking from the new material examined, which included 9 samples from depths of 49—60 m (the collections from below 60 m did not contain the species concerned). Some of these samples were rather large, comprising hundreds of full-grown females. This result is in accordance with the earlier observation that in *P. affinis* summer-breeding is confined to comparatively great depths (Segerstråle 1967). As material is lacking from the zone between 60 m and 100 m, the depth below which breeding at the warm season has been observed, we do not know the exact depth at which such reproduction commences; however, certain facts (*cf.* just-mentioned paper) point to the lower part of the gap in question.

Pontoporeia femorata. Females with freshly deposited eggs were found in collections from all the months sampled. Earlier no such observations had been made in July or August. Whereas in the samples from these months females of the type concerned were few in number, they were more numerous in the material collected during the period from late April to early June. In fact, in some of the samples from this time, the majority of the full-grown females had freshly laid marsupial eggs or swollen ovaries. Such a feature has not been observed before. Another new point observed is the minimum depth of egg-laying during the warm season in Baltic waters, as in one sample, collected in late May at 45 m, a female with freshly deposited eggs was found; as was mentioned above, corresponding records made earlier from the Baltic area refer to *c.* 60 m.

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[1]) For the kind assistance given by the staff of the Station in that connection my sincere thanks are expressed.

SUMMARY AND DISCUSSION

As has emerged, examination of the new material of *P. affinis* and *P. femorata* from Baltic waters has confirmed the earlier conclusions (1) that in this area egg-laying outside the cold season is confined to deep water and (2) that the level at which such reproduction commences is different in the two species, being clearly higher in *femorata*. The new observations accentuate this difference, as indications of incipient breeding were found in this species already at a depth of 45 m (earlier minimum *c.* 60 m).

These results should be compared with those obtained in other parts of the world. As far as *P. affinis* is concerned, no data on propagation outside the cold season are known from other marine areas. By contrast, the phenomenon has been observed in a number of lakes in North America, where, as in the Baltic area, summer-breeding seems to be restricted to greater depths (Segerstråle 1967, 1971 a). In the case of *P. femorata*, a purely marine species, sampling in the Canadian arctic area also indicates that reproduction in shallow water (above 25 m; Steele, *cf.* Segerstråle 1967) does not occur at the warm season. This result is in good accord with recent observations in the White Sea, as collecting work performed there (in Rugozerskaya Bay) above 20 m did not reveal any signs of incipient reproduction in the species during the period May—August (Margulis 1970).

There is thus clear evidence from various parts of their ranges that in both *P. affinis* and *P. femorata* the restriction of breeding to the cold season becomes less pronounced with depth and that in the minimum depth concerned the two species exhibit a difference.

What, then, about the reasons for these phenomena?

In my paper of 1967, it was already suggested that the light factor is involved. Recent experimental work (Segerstråle 1970, 1971 b) has yielded strong support for this conclusion. In populations of *P. affinis* living in comparatively shallow water, the restriction of reproduction to the cold season seems to be due to the maturation of the gonads being induced by the decrease in illumination in late summer. It should be noted that recent field work and experimental studies on the reproductive cycle of the arctic-subarctic amphipod *Gammarus setosus* Dementieva, which also breeds during the cold season, have led to the same conclusion as that arrived at in my work on *Pontoporeia:* »Timing of breeding is evidently independent of temperature, but photoperiod has been found to affect the cycle (V. J. Steele, unpublished observations)» (Steele & Steele 1970, p. 669).

The view that light is the factor responsible would also explain why the widening of the reproductive period of *P. affinis* to include the warm season is confined to deep water, as there practically dark conditions prevail or, at any rate, the seasonal fluctuations of illumination are largely smoothed out and, in consequence, the regulating effect of light on maturation can be concluded to be comparatively weak.

It also seems logical to seek a link between the light factor and the fact that in *P. femorata* breeding during the warm season is observed at a higher level than in *P. affinis*. Two alternative explanations may be considered: (1) the light perception of the eyes of the two species is different (being weaker in *femorata*), or (2) there is no difference in perception, but the effect of the perceived light on the maturation of the gonads (conceivably through neurosecretory processes) is not the same (*femorata* less sensitive). Since recent comparative studies on the perception of light in the two species of *Pontoporeia* under discussion (Donner 1971) have shown that they exhibit practically no difference in this respect, the first of these alternatives seems to be untenable.

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NUMERICAL INVESTIGATION OF THE INFLUENCE OF WIND ON WATER LEVELS AND CURRENTS IN THE GULF OF BOTHNIA: A PRELIMINARY EXPERIMENT

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The Gauss-Seidel iteration method is used and extended to three dimensions to solve a numerical model for calculating water levels and volume transports in the Gulf of Bothnia. One preliminary test has been made and compared with two observed cases. The model seems to be capable of giving at least a rough reproduction of events in the Gulf of Bothnia.

Contents

LIST OF SYMBOLS

Symbol	Explanation
c, d	Numbers giving the distance (in meshwidths) of a coast-near point from the coast
f	Coriolis parameter
f_0	Coriolis parameter value
g	Acceleration of gravity
h	Depth
k	Time step number
m, n	Mesh point coordinates
p	Air pressure
r	Friction coefficient
R	Radius of the Earth
Δs	Mesh width
t	Time
$\mathbf{t}^{o}$	Unit vector tangential to the coast
Δt	Length of the time step
u_0	Current speed component at the water surface
u_a, v_a	Wind speed components
u_g, v_g	Geostrophic wind components
u, v, w	Current velocity components
U, V	Volume transport components
$U_c, \ldots, V_{cx}$	Volume transport components at the coast
w_a	Total wind speed
$\mathbf{W}$	Volume transport vector
$\mathbf{W}_c$, $\mathbf{W}'_c$	Volume transport vector at the coast
x, y, z	Cartesian coordinates
α_g	Difference between the directions of a real wind and a geostrophic wind
γ	Wind stress coefficient
δ	Smoothing factor
Δ_h	Horizontal Laplace operator
ζ	Surface elevation above the mean
η	Cartesian coordinate
λ	Proportionality factor real wind/geostrophic wind
μ	Turbulent eddy viscosity coefficient
ν	Kinematic eddy viscosity
ϱ	Density of water
ϱ_a	Density of air
$\varrho\tau_b^{(x)}$, $\varrho\tau_b^{(y)}$	Bottom stress components

Symbol	
$\varrho\tau_s^{(x)}$, $\varrho_s^{(y)}\tau$	Wind stress components at the sea surface
φ	Latitude
χ	Direction angle of the coast with reference to the direction of x
ω	Angular velocity of the Earth
∇	Nabla operator

1. INTRODUCTION

A number of numerical investigations have been made of the circulation and changes of water levels caused by wind in oceans, sea areas or lakes. A couple of them, the works of Svansson (1959) and Henning (1962), concern the Baltic Sea.

Svansson (1959) treats this sea area as a branching canal, the main part of it extending from the Kattegat to the north of the Gulf of Bothnia, while the Gulf of Finland branches off the Baltic proper. He uses equations which Hansen (1956) had derived for a canal model in a slightly modified form, and transforms them according to Fischer's (1959) numerical scheme. In this model, the motion of the water is induced by the wind and damped by the bottom stress. The water levels computed by the method are partly satisfactory, but some of the calculations show rather large deviations from the observations.

Henning (1962) uses the hydrodynamical method of Hansen (1956, 1962) in his work. This method is based on the vertically integrated hydrodynamical equations and the continuity equation. The calculations are performed in a horizontal network. The area of computation is the total Baltic Sea with the Gulfs. The basin is thought of as closed at the Danish Sounds and the current component perpendicular to the coast line is assumed to be zero. Energy is imparted to the water by the wind and the motion is damped by friction against the bottom. The wind stress is assumed to be proportional to the square of the wind speed and a similar formula is used for the dependence of the bottom stress on the current speed, but the influence of the depth is omitted. The water levels calculated do not agree very well with the observations. The reason for this may lie in the unsuitability of the bottom stress term for varying depths. The complicated form of the sea basin may also introduce some errors.

The purpose of this work is to evolve a method for calculating currents and water levels in the Gulf of Bothnia. The modified vertically integrated hydrodynamical and continuity equations are used. The wind stress is calculated according to Hansen, but another formula is chosen for the bottom stress.

2. DIFFERENTIAL EQUATIONS

The motion of a fluid is mathematically governed by the hydrodynamical equations together with the continuity equation. These can be applied to the water in a certain sea basin. The initial currents and water levels are known, and the motion is subsequently influenced by the coast, the friction against the bottom, wind stress, water elevation at the sea boundaries and some extraneous forces. These conditions guarantee that the equations have only one solution.

2.1 VERTICALLY INTEGRATED HYDRODYNAMICAL EQUATIONS

Hansen (1956) has already integrated the hydrodynamical and continuity equations over the depth. With the addition of the air pressure terms his simplified equations are equivalent to the following

$$\frac{\partial U}{\partial t} - fV = -gh\frac{\partial \zeta}{\partial x} - \frac{h}{\varrho}\frac{\partial p_a}{\partial x} + \tau_s^{(x)} - \tau_b^{(x)} \tag{2.1}$$

$$\frac{\partial V}{\partial t} + fU = -gh\frac{\partial \zeta}{\partial y} - \frac{h}{\varrho}\frac{\partial p_a}{\partial y} + \tau_s^{(y)} - \tau_b^{(y)} \tag{2.2}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0. \tag{2.3}$$

2.2 CORIOLIS TERMS

For practical calculations the Coriolis terms were slightly modified by using the concept of the β-plane. The Coriolis parameter was approximated by

$$f = f_0 + \frac{df}{dn}\delta n \text{ or } f = f_0 + \frac{2\,u\cos\varphi}{R}\delta n. \tag{2.4}$$

The influence of the additional term is in fact rather small, not exceeding two per cent of the value of f in the area under study, the Gulf of Bothnia.

2.3 WIND STRESS TERMS

It is generally assumed that the wind stress is proportional to the square of the wind speed. The latest investigations show that this law is fairly good for moderate wind speeds (Wu 1969). It is not so good for lighter winds, for which a smaller proportionality factor should be used. The winds in this experiment are mainly precisely those of moderate speed for which the law is most suitable, and the lighter winds, for which it is not valid, have in any case a very small influence on the results. Therefore we put

$$\tau_s^{(x)} = \gamma v_a w_a \tag{2.5}$$

$$\tau_s^{(y)} = \gamma u_a w_a. \tag{2.6}$$

Several authors have treated the influence of wind on the water surface. The table below gives values for γ collected (or calculated) from various sources (see Eqns. (2.5), (2.6)).

TABLE 1

Source	$10^6\gamma$
Ekman (1905)	3.2
Palmén and Laurila (1939)	3.1
Prandtl (1942)	1.1 ... 3.6
Hela (1948)	2.4
Sheppard and Omar (1952)	1.3
Fischer (1959)	2.1
Brocks (1962)	1.9
Svansson (1968)	2.0
Wu (1969)	1.9

The values for γ in the table have been determined by different methods. In general, γ is not completely constant, but depends on the wind speed and is higher for higher wind speeds (Defant, 1961: 419—423, Wu, 1969). We have taken $\gamma = 1.9 \cdot 10^{-6}$. This corresponds to a wind speed of about 10 m/s (Wu, 1969). Since the wind in the study area has values both above and below this, the value chosen for γ may be suitable.

The wind in our problem is calculated from the geostrophic wind

$$u_g = -\frac{1}{f\varrho_a}\frac{\partial p_a}{\partial y} \qquad v_g = \frac{1}{f\varrho_a}\frac{\partial p_a}{\partial x}$$

by reducing its speed by a factor λ and rotating its direction *contra solem* by an angle α_g. In this way are obtained

$$u_a = -\frac{\lambda}{f\varrho_a}\left(\sin\alpha_g \frac{\partial p_a}{\partial x} + \cos\alpha_g \frac{\partial p_a}{\partial y}\right) \tag{2.7}$$

$$v_a = \frac{\lambda}{f\varrho_a}\left(\cos\alpha_g \frac{\partial p_a}{\partial x} - \sin\alpha_g \frac{\partial p_a}{\partial y}\right). \tag{2.8}$$

The quantities λ and α_g in equations (2.7), (2.8) depend closely on the stability of the lower layers of the troposphere. When conditions are stable, λ is relatively small and α_g relatively large, but, under unstable conditions and high pressure gradients λ represents values near 1, whilst α_g is almost zero. Values $\lambda = 0.5$ and $\alpha_g = 15°$ were adopted for the numerical calculations.

2.4 BOTTOM STRESS TERMS

The exact law for the bottom stress is not known. Therefore, a number of bottom stress terms of different kinds have been used (see *e.g.* Fischer, 1959, Sündermann, 1966). Svansson (1968) has made a comparison between some types of bottom friction terms using his canal model of the Gulf of Bothnia as the working tool.

The types of terms investigated by him are

$$\tau_b = k_0 W \tag{2.9}$$

$$\tau_b = k_1 \frac{W}{h} \tag{2.10}$$

$$\tau_b = k_2 \frac{W}{h^2} \tag{2.11}$$

$$\tau_b = k_3 \frac{W|W|}{h^2}, \tag{2.12}$$

where the k's are different constants and W the volume transport in question. His method is to optimize the k- and the corresponding γ-values (*cf.* Eqns. (2.5), (2.6)) to find the best fit between the calculated and observed water levels by the method of least squares. In Table 2 the best values for the different k's and the corresponding γ as well as the MSD (Mean Square Deviation) are given separately for three different sections of the study area. In one case values were available for two slightly different subsections of the Bothnian Bay. The values are taken from figures in Svansson's paper (1968). It becomes clear that none of the bottom friction terms is fully satisfactory, because (as already noted by Svansson)

TABLE 2. Optimized k- and γ-values together with the corresponding mean square deviation values of the water levels for different bottom stress laws and sea levels.

	Bothnian Sea	Meren-kurkku	North of Bothnian Bay
$k_0/(10^{-5}s^{-1})$	> 15	8.0	8.8
$10^6\gamma$	> 4	2.2	2.7
MSD/cm	< 4.5	3.0	4.3
$k_1/(10^{-3}ms^{-1})$	~ 3	2.1	~ 2.5; ~ 2.0
$10^6\gamma$	3.8	2.2	~ 2.9; ~ 2.3
MSD/cm	3.7	2.7	~ 4.1; ~ 5
$k_2/(10^{-2}m^2s^{-1})$	~ 6	4.2	5.3
$10^6\gamma$	3.5	2.2	2.9
MSD/cm	4.3	2.6	4.2
$100\ k_3$	~ 3.0	1.6	2.5
$10^6\gamma$	3.5	1.9	2.4
MSD/cm	4.3	2.9	5.4

— different γ-values had to be chosen for different cross sections.

— in the Bothnian Sea the γ-values are much too high. (A proper value lies around $\gamma = 2 \cdot 10^{-6}$).

It is found that the best γ- and MSD-values are obtained in Merenkurkku and that those of the Bothnian Sea are poor. This is to say, all the methods investigated are relatively good for shallow waters but almost invalid for deeper ones. None of the different friction terms is clearly preferable.

In the present experiment, we have used the following bottom stress law

$$\tau_b^{(x)} = rU \tag{2.13}$$

$$\tau_b^{(y)} = rV \tag{2.14}$$

with

$$r = 2\nu/h^2, \tag{2.15}$$

where ν is constant.

This law can be shown to be true in the case of a current with linear profile and constant depth. Let us deal with the case in one horizontal dimension, say x, only. The current profile may be written

$$u = u_0\left(1 + \frac{z}{h}\right). \tag{2.16}$$

Then the volume transport is

$$U = \int_{-h}^{0} u dz = \frac{u_0 h}{2}. \qquad (2.17)$$

When u from (2.16) is inserted into the defining equation

$$\tau_b^{(x)} = \nu \left(\frac{\partial u}{\partial z}\right)_{-h}$$

and u_0 is eliminated by (2.17), then equation (2.13) with (2.15) ensues.

If instead of a linear profile a cosine form is used, then

$$r = \frac{\pi^2 \nu}{4h^2}.$$

This value has already been used in a few papers (see *e.g.* Fischer 1959).

It is well known that the turbulent viscosity varies within wide limits (Defant, 1961: 104). Therefore caution should be exercised in the selection of a value for the kinematic viscosity ν. We have chosen

$$\nu = 0.04 \ m^2s^{-1}.$$

A comparison with the results of Svansson can be made by noting that this friction law (2.13) with the r-value (2.15) is the same as the third of the laws (2.11) he has investigated. This gives

$$k_2 = 2\nu.$$

His values for the Gulf of Bothnia are found in Table 2 and for the Bothnian Sea, Merenkurkku and the north of the Bothnian Bay are, respectively,

$$k_2 = 0.06 \ m^2s^{-1}, \ k_2 = 0.042 \ m^2s^{-1}, \ k_2 = 0.053 \ m^2s^{-1},$$

while the value used in the present study for the whole Gulf of Bothnia is

$$k_2 = 0.08 \ m^2s^{-1}.$$

It is clear that the kinematic eddy viscosity coefficient appearing in the hydrodynamical equations of motion is used only in order to describe the very complex phenomena of the turbulent viscosity in a simple way. It may be regarded as a function of many variables of the surroundings, for example the depth, the velocity of the water, etc. For the sake of simplicity, constant values are often used for the eddy viscosity term, but empirical formulas have also been based on the dependence of the eddy viscosity coefficient on wind speed in the upper water layers as well as on its variability as a function of the depth (Neumann *et al.*, 1966: 196). The dependence of the kinematic eddy viscosity on the wind is rather strong (Neumann *et al.*, 1966: 210). Therefore the present choice of coefficient may not be too bad.

In this connection it may be mentioned that, according to a notion of Platzman (1963), the influence of the friction law is important when the current distribution from bottom to surface is concerned, but is of minor significance, when the motion of a layer as a whole is observed. Therefore, the choice of the law is not of the utmost importance.

2.5 FINAL FORM OF THE VERTICALLY INTEGRATED HYDRODYNAMICAL EQUATIONS

The equations (2.1) . . . (2.3) together with the wind stress terms from (2.5), (2.6) and the bottom stress terms from (2.13) . . . (2.15) constitute our hydrodynamical equations. The Coriolis parameter is determined by (2.4) and if geostrophic wind is needed for wind calculations, then equations (2.7), (2.8) are used.

2.6 INITIAL CONDITIONS AND BOUNDARY CONDITIONS

To obtain a specific solution of equations (2.1) . . . (2.3), the initial and boundary conditions have to be taken into account. In this model

— the water level elevations and the volume transports are given at the beginning of the calculations.

— the water level elevations at the sea boundaries, *i.e.* at the boundaries of other sea areas, are always given.

— the flow of the water is always parallel to the coast at the land boundaries.

3. NUMERICAL MODEL

The first step in performing numerical calculations is to discretize the data fields, *i.e.* to replace all continuous fields with data picked up from regularly spaced points or determine some averaged values instead and use only them in calculations. To this end, the sea area in question is covered by an array of points, the grid. The form of the meshes is usually a square and calculations are performed at mesh points only. Therefore, derivatives are replaced by corresponding finite differences and centered ones are mostly used to quarantee a good approximation. A usual method is to use different grids for water elevation and volume transport components, and to calculate the water elevation at a different time point than the volume transport components (Hansen, 1962, Fischer, 1965).

The calculations themselves are begun using data of the initial state of the sea in the discretized equations and solving the water elevation and volume transport components consecutively point by point. When all desired fields are obtained, the next time step may be initiated. The calculations proceed in this manner and after each step the boundary conditions are taken care of. They dictate the behaviour of the volume transport at the coasts and the elevation of the water level at the sea boundaries.

3.1 HORIZONTAL GRID

The sea area under study, the Gulf of Bothnia, is presented in Fig. 1 and the horizontal square grid used is shown in Fig. 2.

The grid is determined by the equations

$$x = m\Delta s, \; m = 1, 2, \ldots$$

$$y = n\Delta s, \; n = 1, 2, \ldots$$

In the same way, time is written

$$t = k\Delta t, \; k = 0, 1, \ldots$$

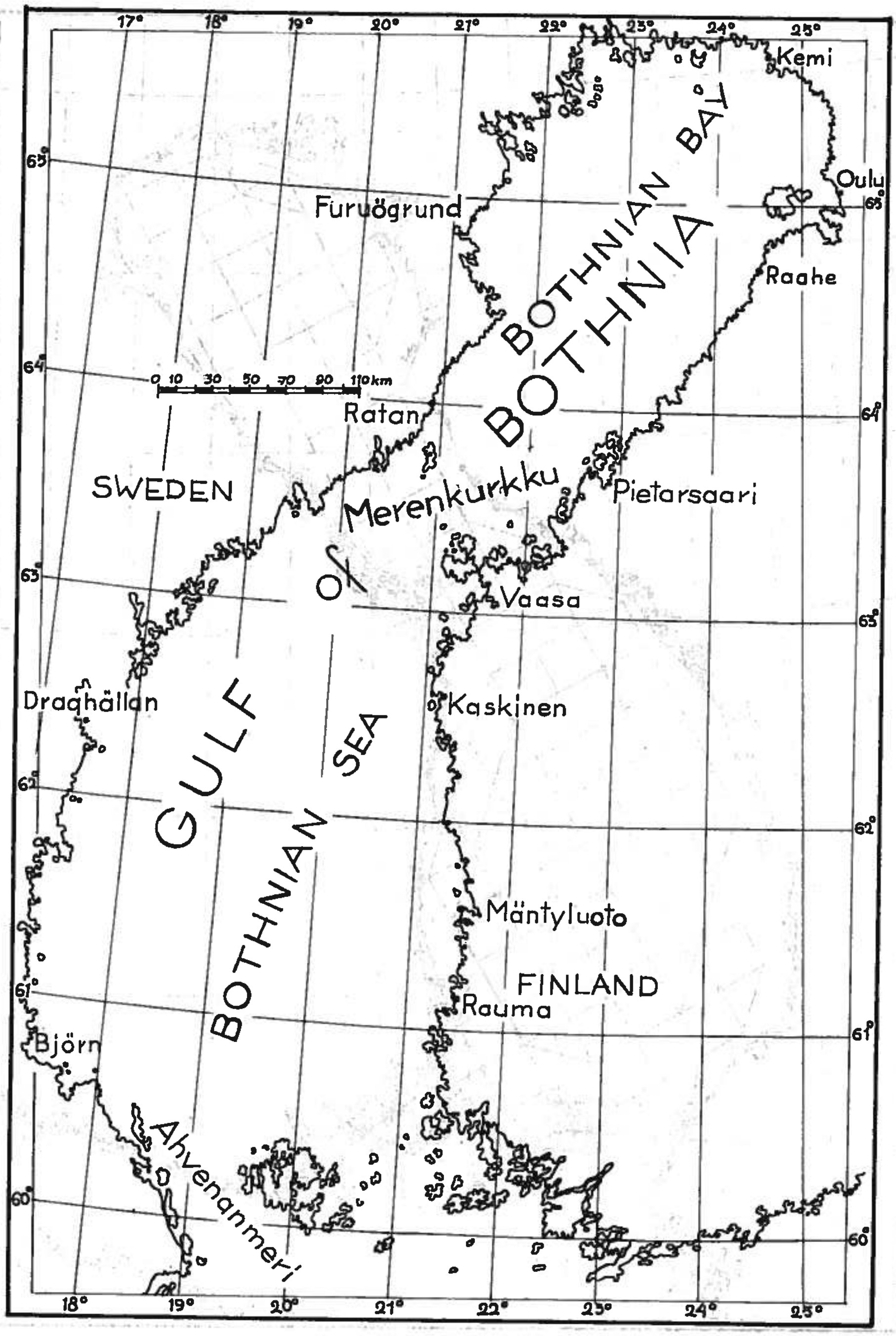

Fig. 1. A map showing the Gulf of Bothnia and the positions of the tide gauges on its coasts.

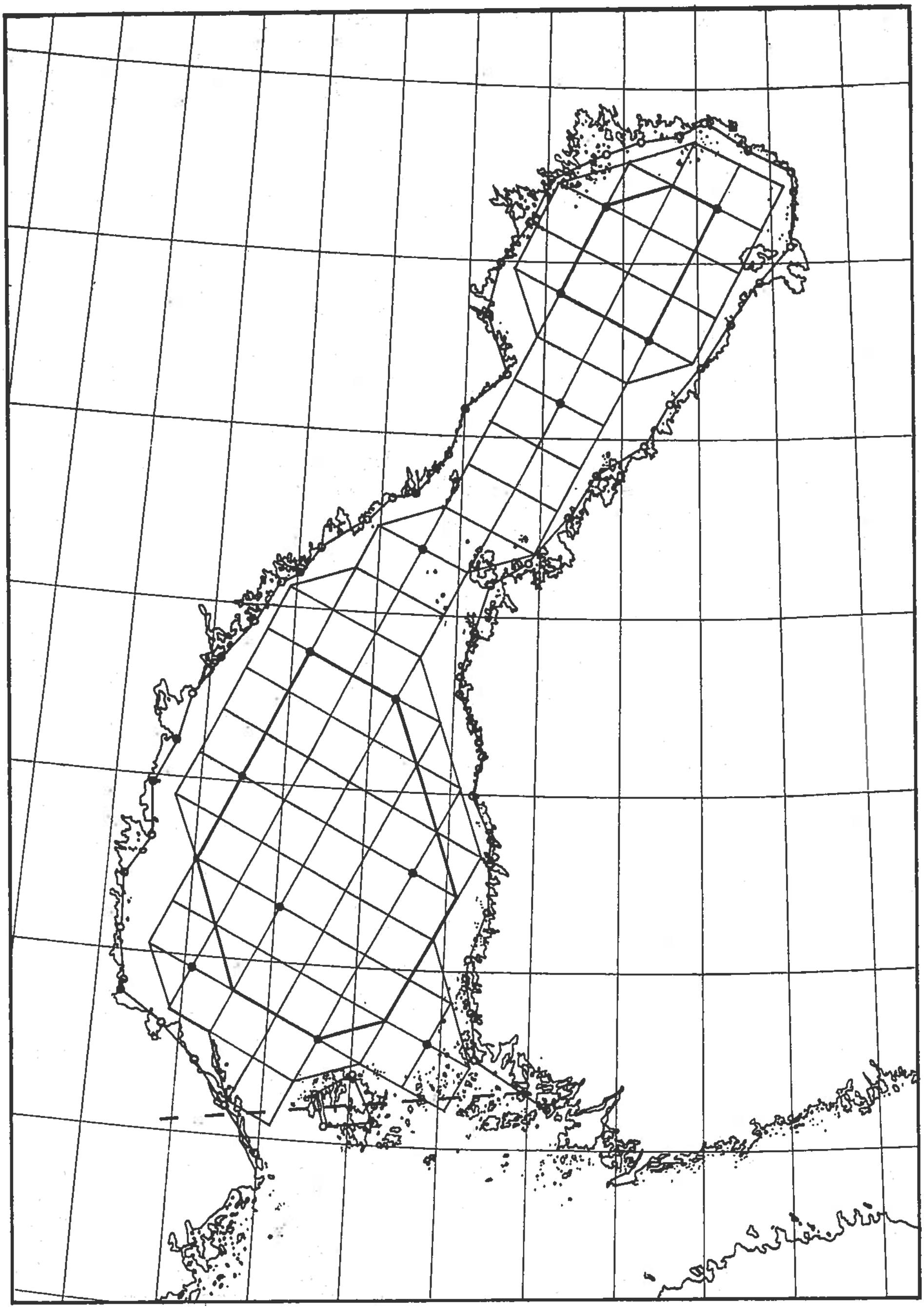

Fig. 2. Network for the computations. Points used for the determination of the movements of water particles as well as loops for studying circulation are also plotted.

This choice transforms continuous functions to functions determined at mesh points only.

For example

$$U(x, y, t) = U^{(k)}_{m,n} = U(m\Delta s,\ n\Delta s,\ k\Delta t).$$

This way of approximating the derivatives leads to differences. In order to obtain good approximations for internal grid points, centred difference formulas are used. Thus

$$\frac{\partial U}{\partial x} = \frac{U^{(k)}_{m+1,n} - U^{(k)}_{m-1,n}}{2\Delta s}.$$

Forward finite differences of the type

$$\frac{\partial U}{\partial x} = \frac{U^{(k)}_{m+1,n} - U^{(k)}_{m,n}}{\Delta s}$$

are chosen, when $U^{(k)}_{m-1,n}$ falls outside the calculation area. The backward finite differences are used in a similar manner.

The direction chosen for the x-axis of the coordinate systems was that of the lengthwise trend of the Gulf of Bothnia; more exactly, the direction angle chosen was 205.9°, and the z-axis was taken as pointing vertically upwards (See Figs. 1 and 2). The orientation of the grid has no influence on the results.

Navigation charts were used to obtain the shorelines and bathymetric data of the Gulf of Bothnia (see Fig. 2). A depth value was allotted to each grid point, which was a mean value for a circular area with the mesh width as diameter (*cf.* Fig. 3). The total number of points covering the area investigated is 106. Of these 45 lie close to the coast and only two at the sea boundary.

The real coastline was approximated as nearly as possible by additional points which were the intersections of the simplified coastline and the principal lines of the square network. The number of these points is 66.

3.2 FINITE-DIFFERENCE EQUATIONS

According to the principles explained above and the observations made in section 2.6, the hydrodynamical equations (2.1) . . . (2.3) are transformed into

$$\frac{U^{(k+1)}_{m,n} - U^{(k)}_{m,n}}{\Delta t} = -gh\,\frac{\zeta^{(k)}_{m+1,n} - \zeta p^{(k)}_{m-1,n}}{2\Delta s} - \frac{h}{\varrho}\,\frac{p^{(k)}_{m+1,n} - p^{(k)}_{m-1,n}}{2\Delta s} \tag{3.1}$$

$$+ fV^{(k)}_{m,n} + \gamma u_a w_a - rU^{(k)}_{m,n}$$

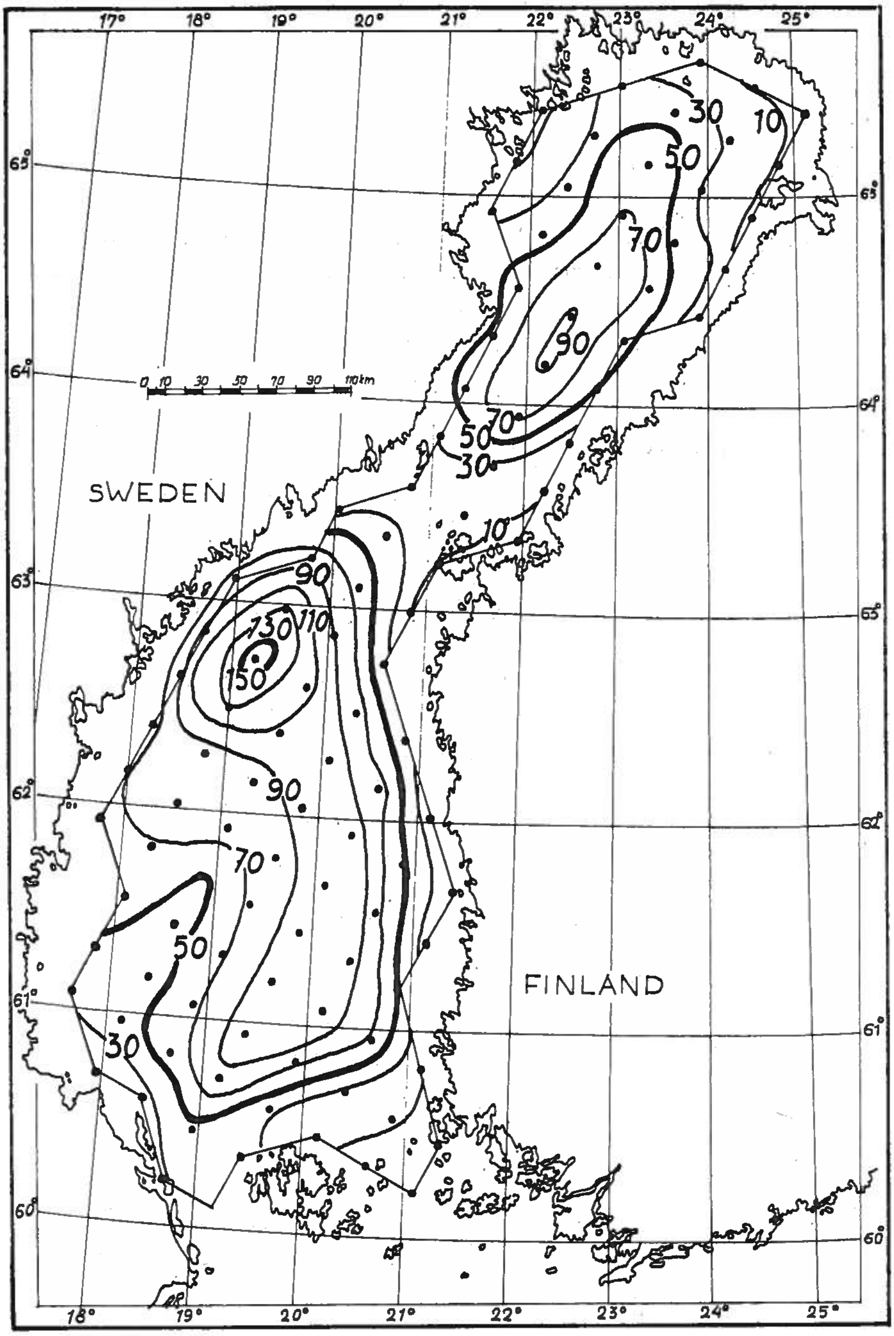

Fig. 3. Depths of the Gulf of Bothnia (in metres) as used in the computations.

$$\frac{V^{(k+1)}_{m,n} - V^{(k)}_{m,n}}{\Delta t} = -gh\frac{\zeta^{(k)}_{m,n+1} - \zeta^{(k)}_{m,n-1}}{2\Delta s} - \frac{h}{\varrho}\frac{p^{(k)}_{m,n+1} - p^{(k)}_{m,n-1}}{2\Delta s} \tag{3.2}$$

$$-fU^{(k)}_{m,n} + \gamma v_a w_a - rV^{(k)}_{m,n}$$

$$\frac{\zeta^{(k+1)}_{m,n} - \zeta^{(k)}_{m,n}}{\Delta t} = -\frac{U^{(k)}_{m+1,n} - U^{(k)}_{m-1,n}}{2\Delta s} - \frac{V^{(k)}_{m,n+1} - V^{(k)}_{m,n-1}}{2\Delta s}. \tag{3.3}$$

These equations can be solvedf or $U^{(k+1)}_{m,n}$, $V^{(k+1)}_{m,n}$, $\zeta^{(k+1)}_{m,n}$ and used already in this form to calculate ζ-, U-, V-fields step by step.

A solution method is iterative, if it uses the first approximation to solve the second one, then uses the second to determine the next one and so on.

Let us consider a difference equation

$$\frac{f^{(k+1)}_m - f^{(k)}_m}{\Delta t} = \sum_i a_i f^{(k)}_i + b_m \tag{3.4}$$

with two dimensions, length and time. It is assumed that i can have only a few values in the neighbourhood of m.

It is clear that the following equation is more accurate

$$\frac{f^{(k+1)}_m - f^{(k)}_m}{\Delta t} = \frac{1}{2}\sum_i (a_i f^{(k+1)}_i + f^{(k)}_i) + b_m$$

or, since the $f^{(k)}_i$'s are known,

$$\frac{f^{(k+1)}_i - f^{(k)}_m}{\Delta t} = \frac{1}{2}\sum_i a_i f^{(k+1)}_i + c_m$$

with

$$c_m = b_m + \frac{1}{2}\sum_i a_i f^{(k)}_i.$$

The equation is solved by iteration, according to the Gauss-Seidel method,

$$f^{(k+1)}_m = \frac{f^{(k)}_m + \frac{\Delta t}{2}\sum_{i \neq m} a_i f^{(k+1)}_i + c_m \Delta t}{1 - \frac{a_m \Delta t}{2}} \tag{3.5}$$

(see Smith, 1965: 26—27, 147—149). An important feature of this method is that old values are immediately replaced by new ones. The procedure is naturally continued until the desired accuracy is reached.

Our equations have more unknown functions than is presumed by the original Gauss-Seidel method, but it is easily expansible to this case. After transformation equations (3.1) . . . (3.3) read

$$U_{m,n}^{(k+1)} = \frac{1}{1+r\Delta t/2}\Bigg[U_{m,n}^{(k)} + \frac{\Delta t}{2}\Bigg(-gh\frac{\zeta_{m+1,n}^{(k)} - \zeta_{m-1,n}^{(k)}}{2\Delta s} - \frac{h}{\varrho}\frac{p_{a\,m+1,n}^{(k)} - p_{a\,m-1,n}^{(k)}}{2\Delta s}$$

$$+ fV_{m,n}^{(k)} + \gamma u_{a\,m,n}^{(k)} w_{a\,m,n}^{(k)} - rU_{m,n}^{(k)} - gh\frac{\zeta_{m+1,n}^{(k+1)} - \zeta_{m-1,n}^{(k+1)}}{2\Delta s} - \frac{h}{\varrho}\frac{p_{a\,m+1,n}^{(k+1)} - p_{a\,m-1,n}^{(k+1)}}{2\Delta s}$$

$$+ fV_{m,n}^{(k+1)} + \gamma u_{a\,m,n}^{(k+1)} w_{a\,m,n}^{(k+1)} - r\,U_{m,n}^{(k+1)}\Bigg)\Bigg] \tag{3.6}$$

$$V_{m,n}^{(k+1)} = \frac{1}{1+r\Delta t/2}\Bigg[V_{m,n}^{(k)} + \frac{\Delta t}{2}\Bigg(-gh\frac{\zeta_{m,n+1}^{(k)} - \zeta_{m,n-1}^{(k)}}{2\Delta s} - \frac{h}{\varrho}\frac{p_{a\,m,n+1}^{(k)} - p_{a\,m,n-1}^{(k)}}{2\Delta s}$$

$$- fU_{m,n}^{(k)} + \gamma v_{a\,m,n}^{(k)} w_{a\,m,n}^{(k)} - rV_{m,n}^{(k)} - gh\frac{\zeta_{m,n+1}^{(k+1)} - \zeta_{m,n-1}^{(k+1)}}{2\Delta s} - \frac{h}{\varrho}\frac{p_{a\,m,n+1}^{(k+1)} - p_{a\,m,n-1}^{(k+1)}}{2\Delta s}$$

$$- fU_{m,n}^{(k+1)} + \gamma v_{a\,m,n}^{(k+1)} w_{a\,m,n}^{(k+1)} - r\,V_{m,n}^{(k+1)}\Bigg)\Bigg] \tag{3.7}$$

$$\zeta_{m,n}^{(k+1)} = \zeta_{m,n}^{(k)} - \frac{\Delta t}{4\Delta s}\Big(U_{m+1,n}^{(k)} - U_{m-1,n}^{(k)} + V_{m+1,n}^{(k)} - V_{m-1,n}^{(k)} + U_{m+1,n}^{(k+1)} - U_{m-1,n}^{(k+1)}$$

$$+ V_{m+1,n}^{(k+1)} - V_{m-1,n}^{(k+1)}\Big). \tag{3.8}$$

Because of the implicit nature of equations (3.6) . . . (3.8), all quantities on the right-hand sides are not known and approximations are used instead. As the starting values of a certain iteration procedure, the results of the foregoing time step are taken. To minimize the number of poorly known quantities, the water elevations were calculated first and the volume components afterwards.

The convergence of the iteration was rather good. Two iteration steps were used in the model throughout, and yet the iteration errors in water levels generally remained below one per cent of the values. In a few instances this goal was not quite achieved, and a third iteration step should have been used.

3.3 BOUNDARY CONDITIONS

3.3.1 Land boundary

Near the coast, the current must be parallel to the coastal line. This condition is realized by replacing the volume transport vector $\mathbf{W}_c$ at each actual point by a vector

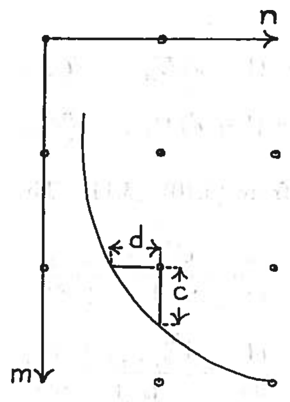

Fig. 4. Distances from the outermost grid points to the coastline.

$\mathbf{W}'_c$ which is parallel to the coast and has the magnitude of the component of $\mathbf{W}_c$ parallel to the coast:

$$\mathbf{W}'_c = \mathbf{t}^\circ \mathbf{t}^\circ \cdot \mathbf{W}. \tag{3.9}$$

The components of $\mathbf{W}'_c$ are

$$U'_c = \cos\chi\,(U_c \cos\chi + V_c \sin\chi) \tag{3.10}$$

$$V'_c = \sin\chi\,(U_c \cos\chi + V_c \sin\chi). \tag{3.11}$$

This condition halts the motion perpendicular to the coast but allows the current component parallel to the coast to flow undisturbed.

Since, in the present case, none of the coastal points belong to the grid system, where calculations normally take place, U_c and V_c must be determined by extrapolation from grid values nearby. The new values U_c, V_c are needed only in (3.8). Therefore, we calculate the derivatives $\frac{\partial U}{\partial x}$, $\frac{\partial V}{\partial y}$ directly from these values and the known values nearby.

The distance between a grid point (m, n) near the coast and the nearest points on the coast lying on the corresponding mesh lines are divided by the mesh width, Δs. The results are denoted by c and d in the x- and y-directions respectively (see Fig. 4). Then linear extrapolation in the x-direction gives

$$U_{cx} = (1 + c)\,U_{m,n} - cU_{m-1,n} \tag{3.12}$$

$$V_{cx} = (1 + c)\,V_{m,n} - cV_{m-1,n} \tag{3.13}$$

and in the y-direction

$$U_{cy} = (1 + d)\, U_{m,\,n} - dU_{m,\,n+1} \tag{3.14}$$

$$V_{cy} = (1 + d)\, V_{m,\,n} - dV_{m,\,n+1}\,. \tag{3.15}$$

Then U'_{cx} and V'_{cy} are found from (3.10), (3.11). The required derivatives are thus

$$\frac{\partial U}{\partial x} = \frac{U'_{cx} - U_{m-1,\,n}}{\Delta s\,(1 + c)} \tag{3.16}$$

$$\frac{\partial V}{\partial y} = \frac{V_{m,\,n+1} - V'_{cy}}{\Delta s\,(1 + c)} \tag{3.17}$$

in the specific case indicated by the figure.

Before arriving at this procedure, another idea was tried. It was assumed that the current right at the coastline was zero. However, it was found that the volume transports and the water levels, behaved unsatisfactorily, especially at the points nearest to the coastline, and as time went on, they disturbed the whole configuration. That is to say, the method was unstable. Therefore, the idea was abandoned.

3.3.2 Sea boundary

The sea area under study is not bounded only by land, but also by adjacent sea areas. The boundaries of such contiguous sea areas are called sea boundaries. At the sea boundaries the only boundary condition given is the water level and in this experiment it was simply assumed to be zero.

3.4 STABILITY OF THE MODEL

Several authors (Fischer, 1959, Schmitz, 1965) have shown by the Fourier method (Lax *et al.*, 1956, Smith, 1965) that equations similar to (2.1) . . . (2.3) form a stable equation system if the Courant-Friedrich-Lewy criterion

$$\sqrt{gh}\,\frac{\Delta t}{\Delta s} < \sqrt{2} \tag{3.18}$$

for a simple wave equation is fulfilled. However the Fourier method considers only internal points of the area in question and thus omits the boundary conditions altogether. This drawback could be avoided by using the matrix method (Smith, 1965). Yet, the matrix to be treated in this case is quite large, containing 315 × 315 elements, and the solution of eigenvalues is not very attractive even when electronic computers are used. Since the stability properties of the model are solely determined by the boundary conditions and the bottom topography, which is contained in the friction term, the Fourier method does not give any useful criteria of the stability of the model. Certain measures were taken to make the equations stable. One of these, the Gauss-Seidel method, has already been described. It is fairly effective in reducing instability, also in the case of difficult areas with shallows, or boundary points with small c or d values (*cf.* Fig. 4). The derivatives at the boundaries were calculated using the two nearest points available. An experiment with three consecutive points was made, but although this method seemed attractive at first, it was abandoned because of instabilities formed in one area in the northwest of the Bothnian Bay.

Nevertheless, the use of the Gauss-Seidel method did not render the model sufficiently stable and stabilizing terms (Fischer, 1959) were added to values obtained from (3.6 . . . (3.8). They are all of the same form. For ζ, for example, the additional term reads:

$$\delta \Delta_h \zeta = \delta \left(\zeta^{(k)}_{m+1,\,n} + \zeta^{(k)}_{m,\,n+1} + \zeta^{(k)}_{m-1,\,n} + \zeta^{(k)}_{m,\,n-1} - 4\zeta^{(k)}_{m,\,n}\right). \tag{3.19}$$

This procedure was completed only when all the values for a certain time step were obtained. For the factor δ a value as large as 0.1 had to be chosen. As is generally known, terms of the form (3.19) have an effect similar to the lateral internal friction. They have a tendency to attenuate shorter waves more strongly than longer ones.

Platzman (1963) has pointed out that a friction law similar to ours may not guarantee the stability of the equations. This may be one reason why the adoption of smoothing terms similar to (3.19) turned out to be necessary.

The choice of the size of the steps used is not free, because the Courant-Friedrich-Lewy criterion (3.18) must always be fulfilled to guarantee the stability of the model. The accuracy to be obtained is another restricting factor. In view of these considerations, we have taken $\Delta s = 30.6$ km and $\Delta t = 6$ min (see Fig. 3).

The model is stable at least during the calculation time of 14 hours, corresponding to 140 time steps, but it may be stable much longer, judging from the behaviour of the instabilities for small δ-values.

4. SPECIFICATION OF THE WIND STRESS

In order to test the crude features of the model, a very simple time-dependent pressure/wind-forcing function was taken for the preliminary experiment. A pressure gradient was chosen in such a way that the wind, computed according to equations (2.7), (2.8), had a direction coinciding with the lengthwise trend of the Gulf of Bothnia. The intention was to use a sine-like function for the time-dependence of the forcing function, but because of an error in programming, the air pressure in the model became different. The corresponding wind computed from equations (2.7), (2.8) is seen in Fig. 5. Despite of the peculiarity of the forcing function implied, it was at first retained to develop the programme further and then also to analyse the results from the preliminary experiment.

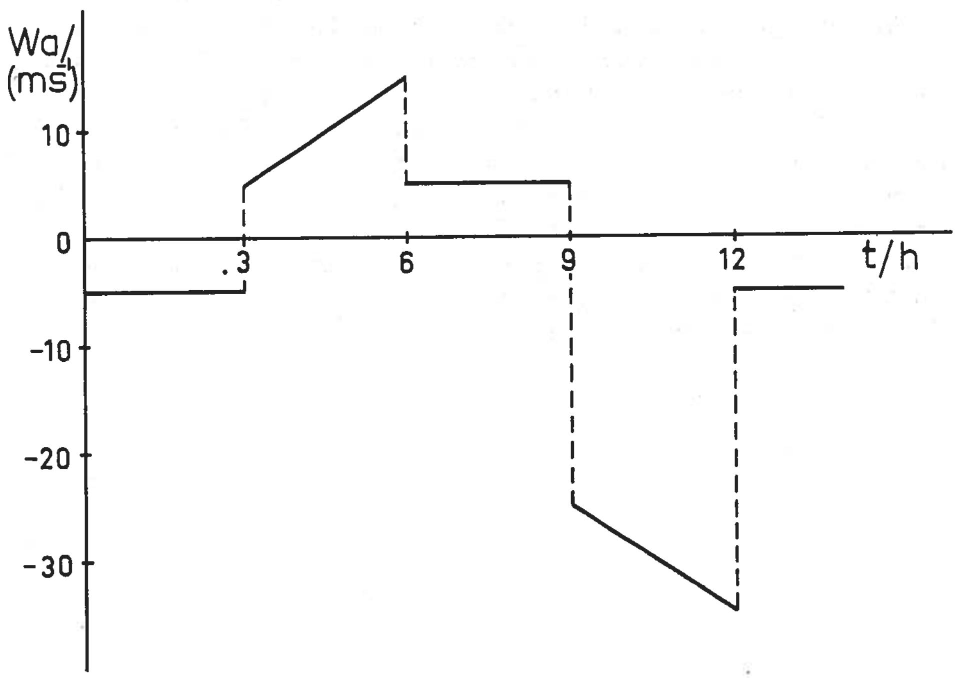

Fig. 5. Wind speed as a function of time.

5. RESULTS

5.1 WATER LEVEL AND VOLUME TRANSPORT

The calculations comprise a time of 14 hours. At the beginning the water elevation and the currents were taken as equal to zero. The results are plotted in Figures 6 . . . 9. The deviation from the linear to and fro motion of the water induced by pure wind action is caused by the Coriolis force, the specific shape of the basin of the Gulf of Bothnia and the air pressure.

The Coriolis force tends to rotate the direction of the motion to the right, but near the coast the water movement cannot pass the coastline and become parallel to it. In the calculations the coastline is represented by a polygon drawn to approximate as closely as possible to the real coast (see Fig. 2). The water level at the sea boundary in the south was assumed to be zero. For this reason, rather strong currents are obtained in this area in the present experiment.

Air pressure induces flow in a direction almost perpendicular to that of wind stress. If the pressure gradient points south-east, say, then the pressure term in equations (2.1), (2.2) causes the waters to flow north-west, but the direction in which the wind is blowing is about north—north-east. When their respective magnitudes are compared in equations (2.1), (2.2), it is observed that the air pressure term grows linearly with the pressure gradient, but the growth of the wind stress term is quadratic. In Table 3 the magnitudes of these terms are calculated for some wind speeds. It is noted that for lighter winds the air pressure term is larger than the wind stress term, but for winds stronger than 5.3 m/s the opposite is true.

TABLE 3. Comparison of pressure term and wind stress term.

$v_a/(\mathrm{ms^{-1}})$	$10^5 T_{p_a}/(\mathrm{m^2s^{-2}})$	$10^5 T_{\tau_s}/(\mathrm{m^2s^{-2}})$
2	2.03	0.76
4	4.06	3.04
6	6.08	6.84
8	8.11	12.16
10	10.14	19.00

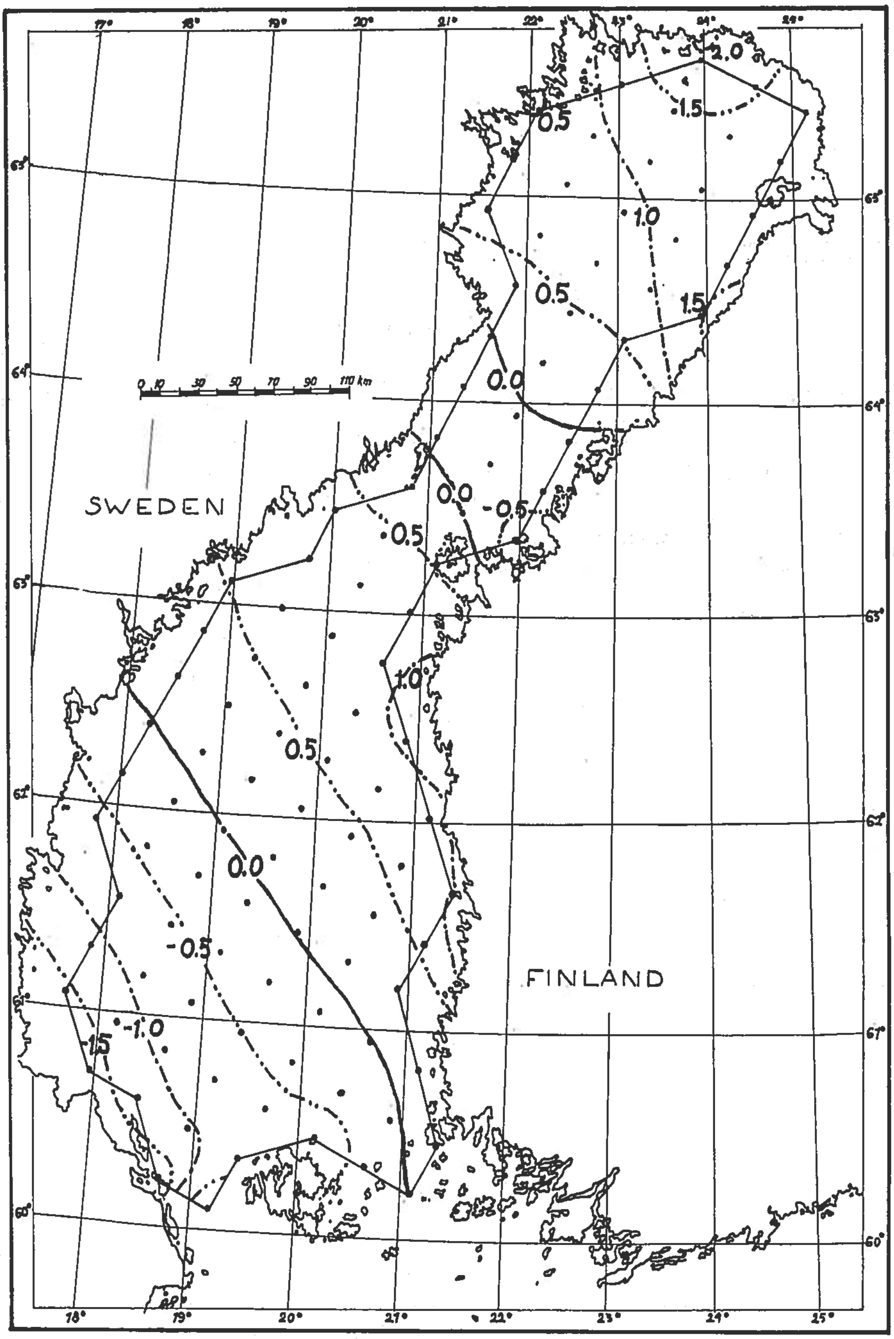

Fig. 6 a. Water levels (in cm) three hours after the beginning of the experiment.

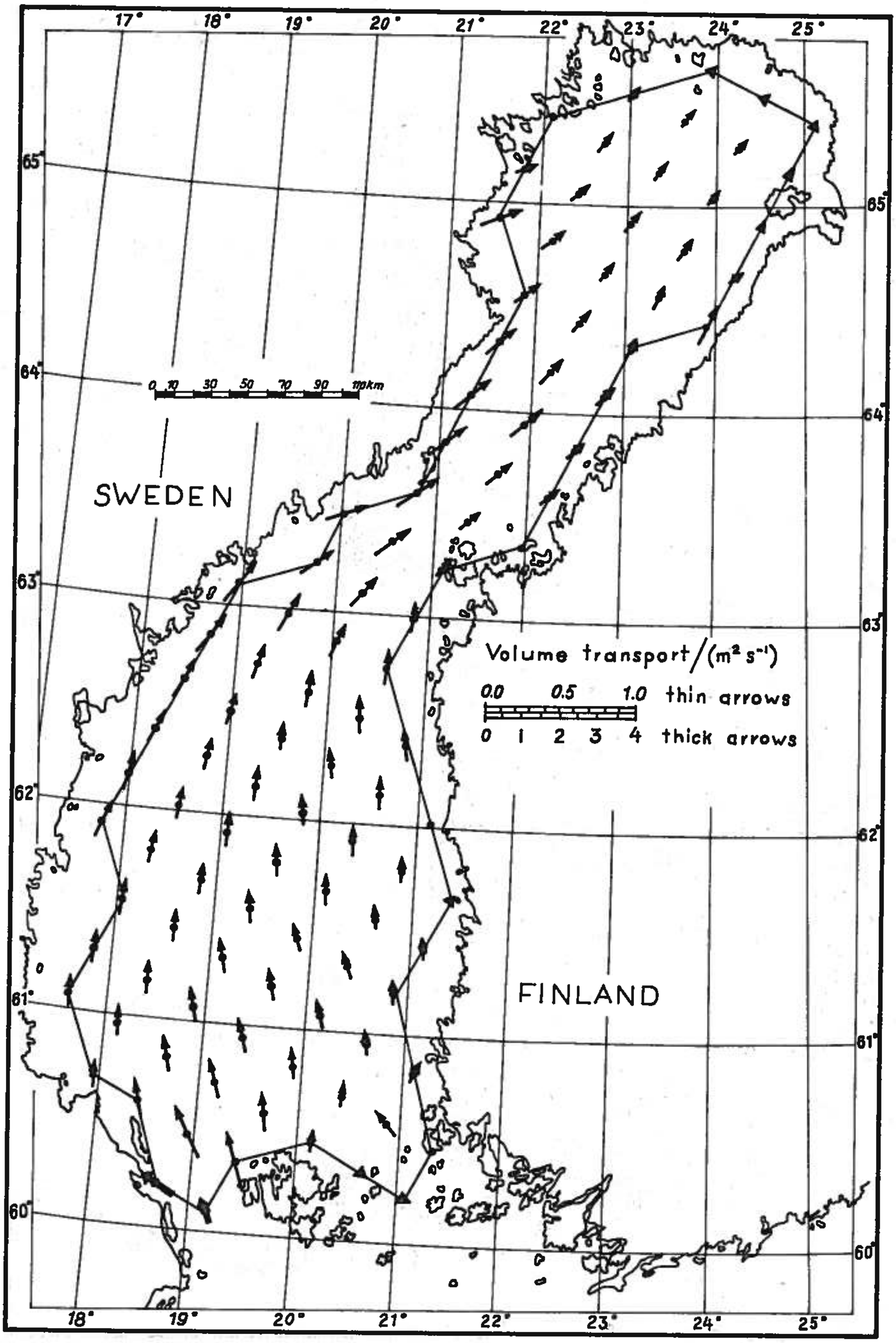

Fig. 6 b. Volume transports three hours after the beginning of the experiment.

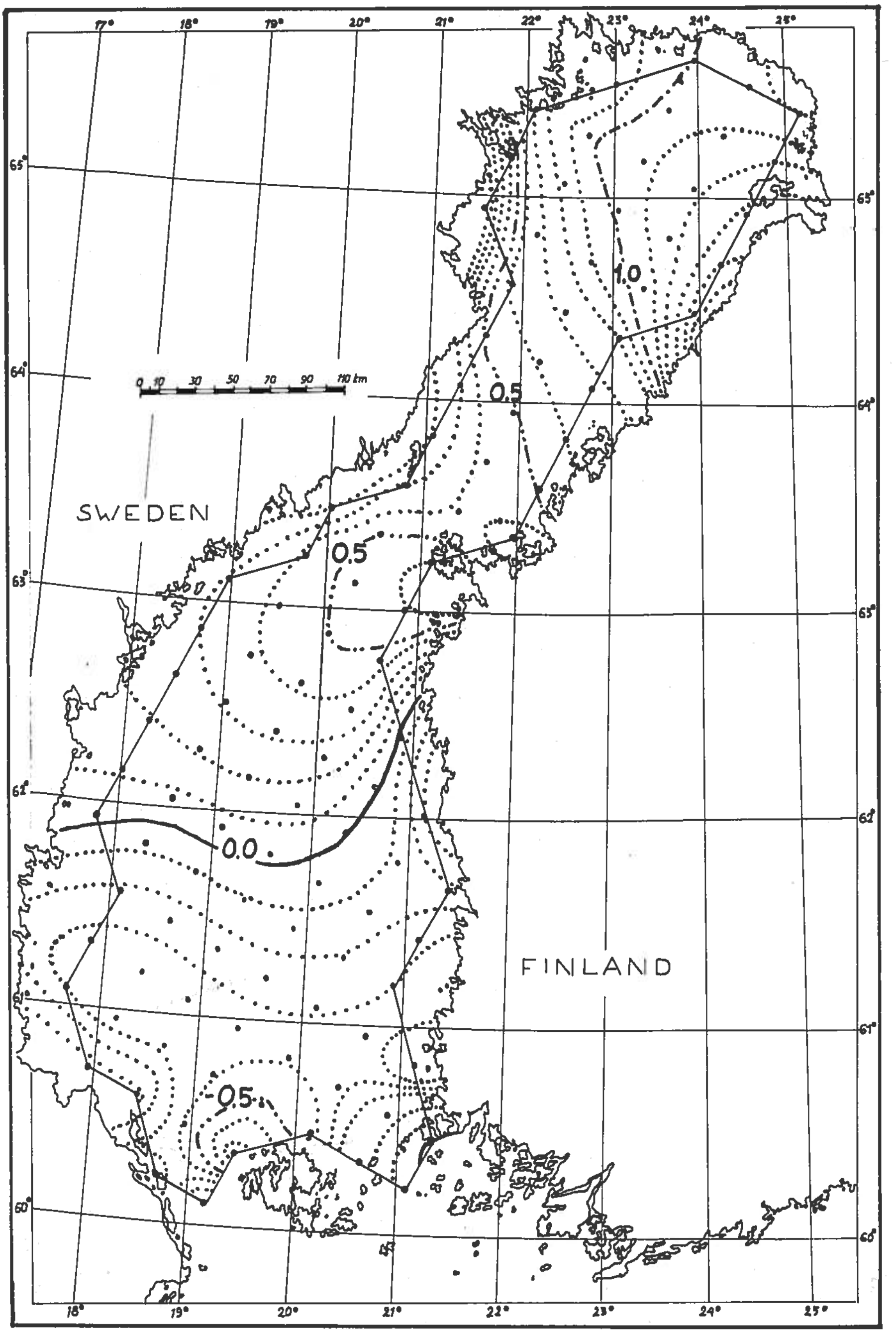

Fig. 7 a. Water levels (in cm) four hours after the beginning of the experiment.

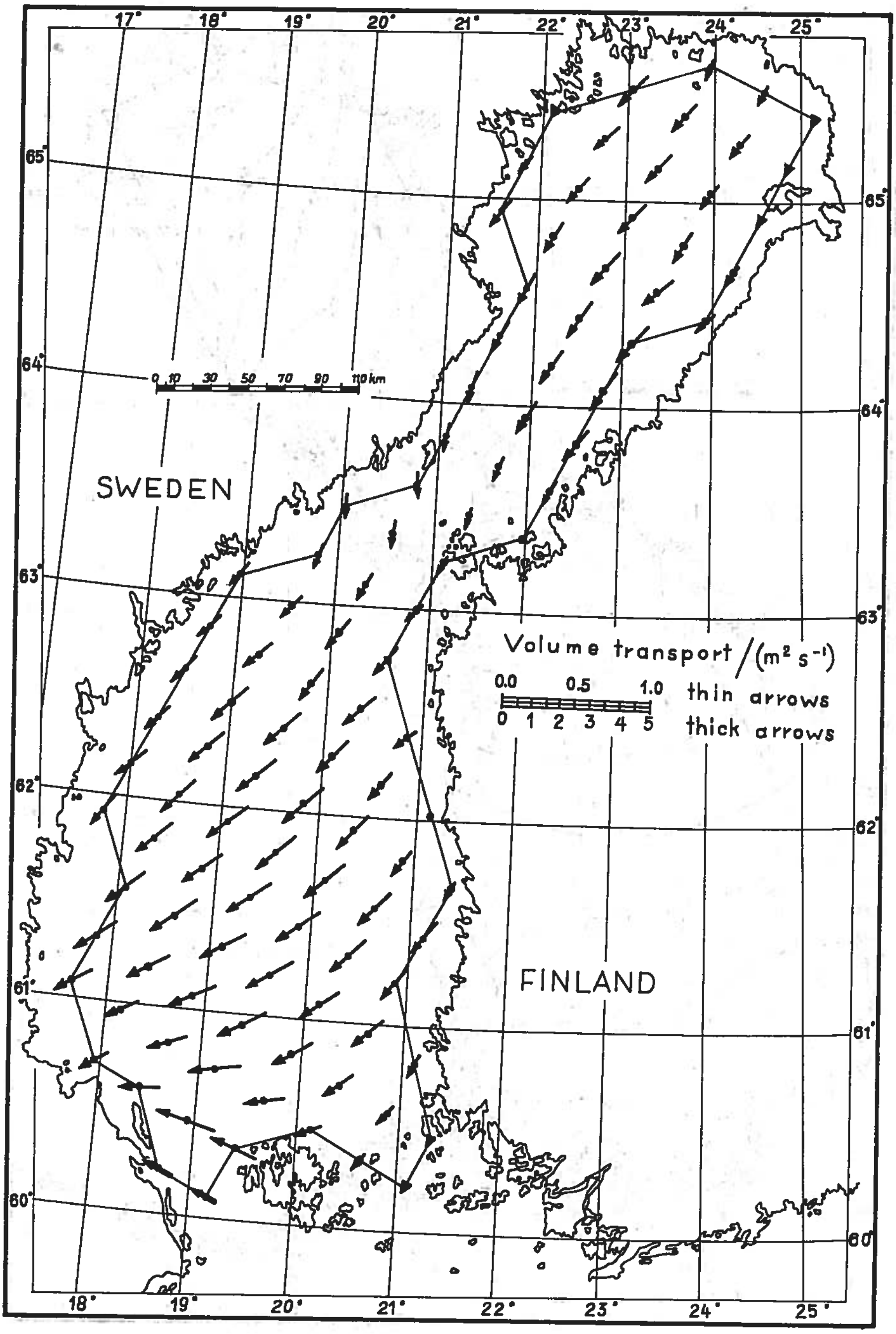

Fig. 7 b. Volume transports four hours after the beginning of the experiment.

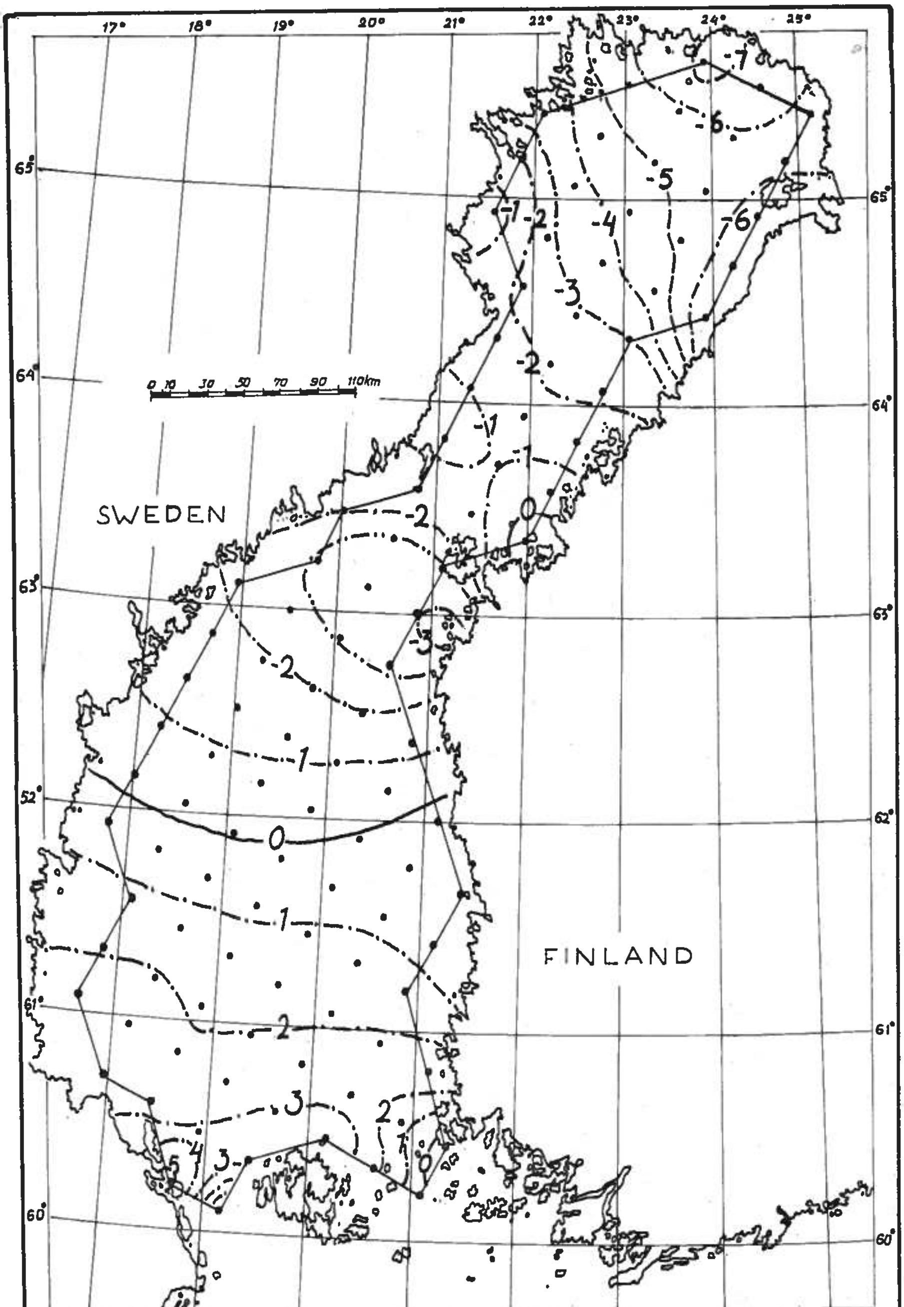

Fig. 8 a. Water levels (in cm) eight hours after the beginning of the experiment.

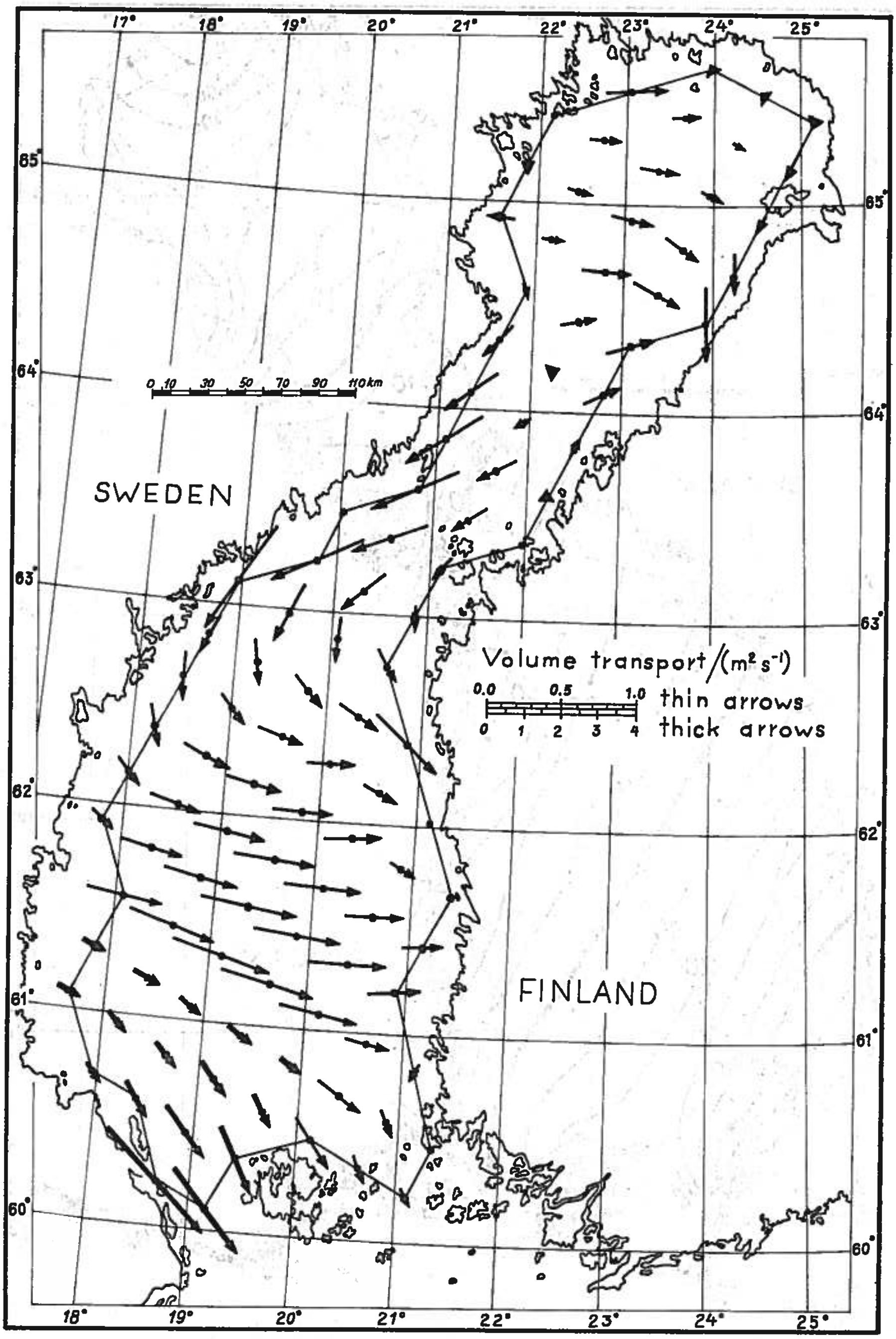

Fig. 8 b. Volume transports eight hours after the beginning of the experiment.

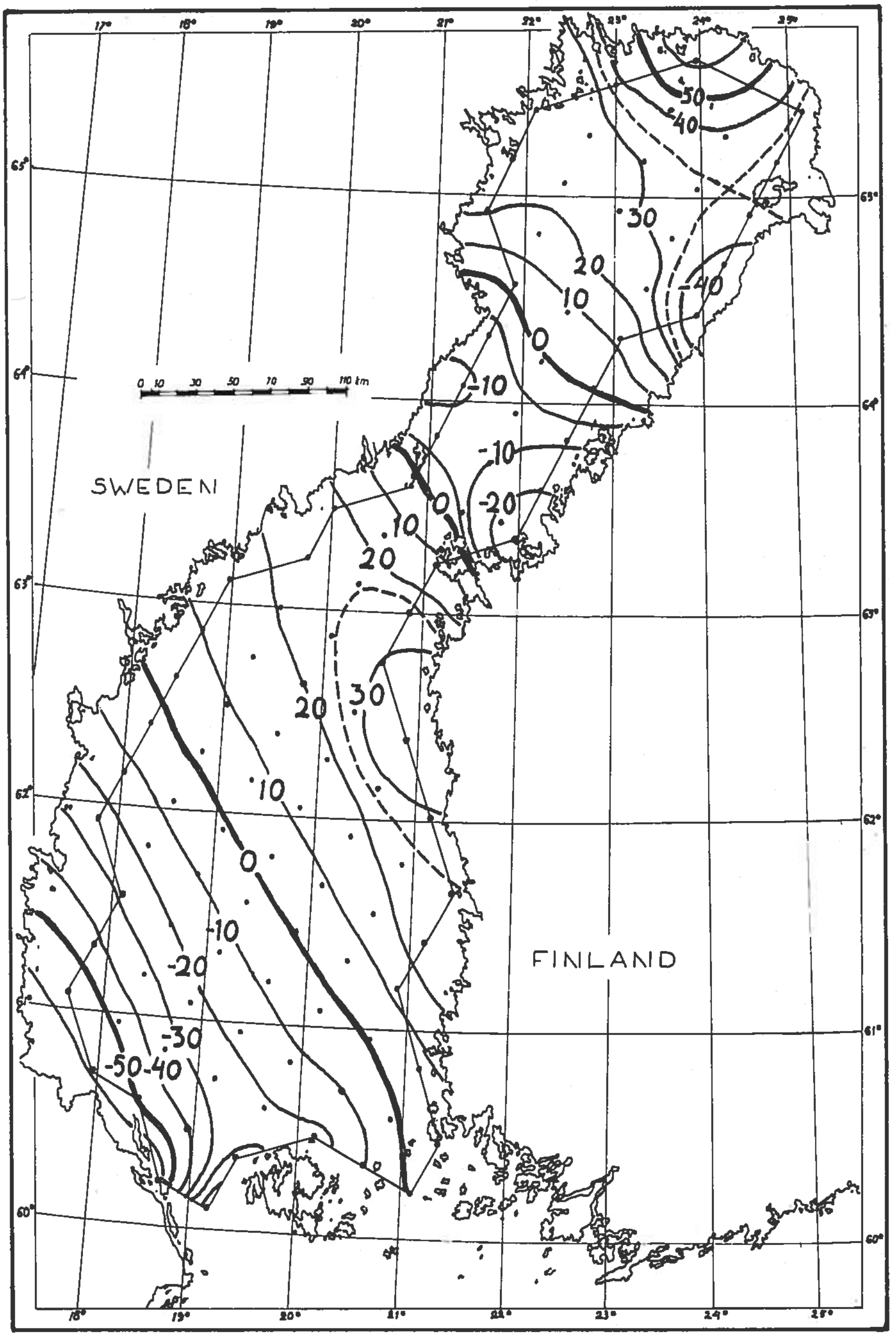

Fig. 9 a. Water levels (in cm) twelve hours after the beginning of the experiment.

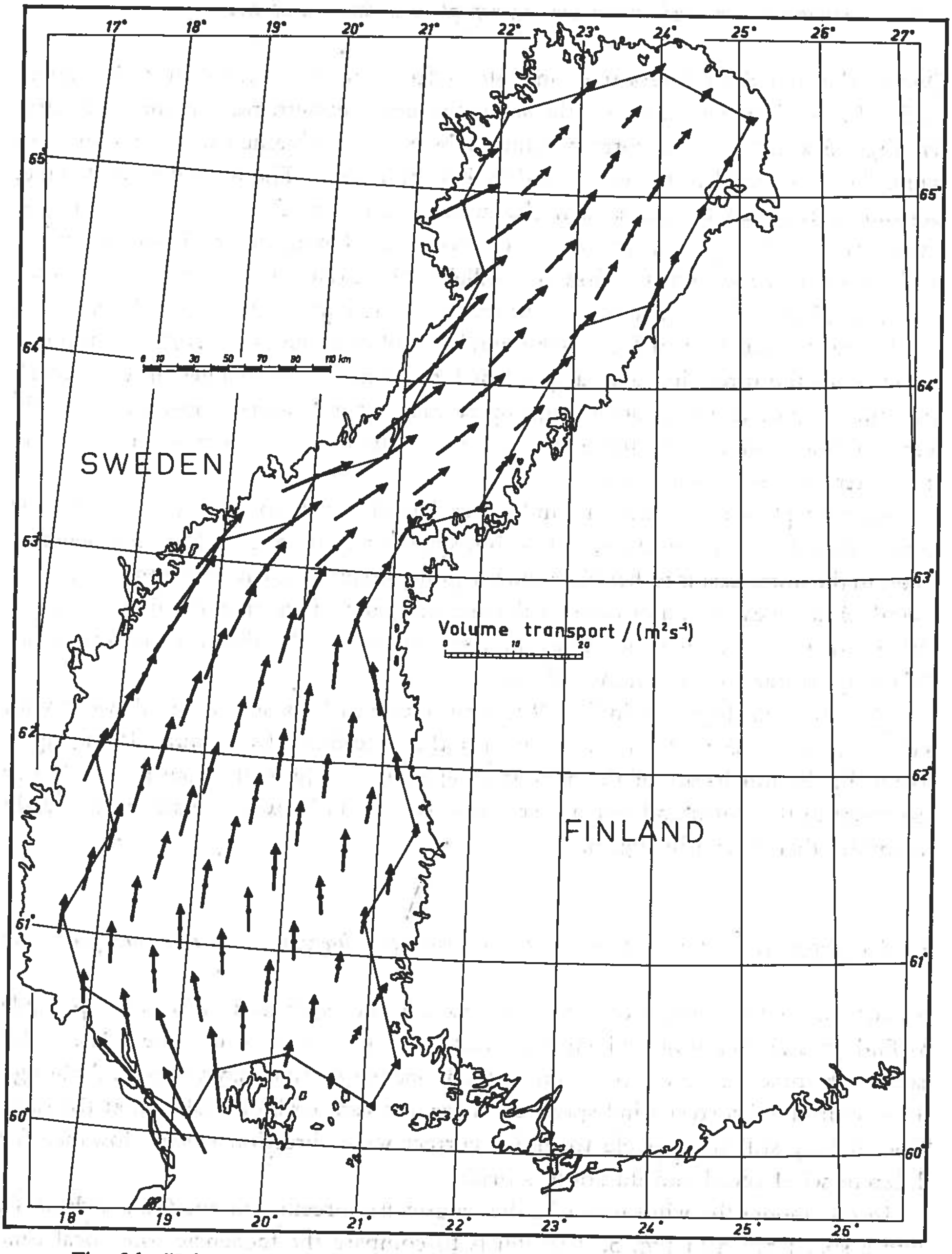

Fig. 9 b. Volume transports twelve hours after the beginning of the experiment.

5.1.1 Computed water level and volume transport as a function of tim

During the first three hours the wind blows from south—south-west with a speed of 5 m/s, causing the water to pile up in the north-eastern part of the study area (*cf.* Figs. 5 and 6.) and a corresponding subsidence is obtained in the south-west, while the water level at the sea boundary is kept at zero. The influence of stronger bottom friction can be seen as a slight subsidence north of Merenkurkku. Volume transport is relatively uniform over the whole area. Owing to the influence of the land boundary conditions the flow is parallel to the coast (the boundaries are shown in Fig. 2). The sea boundary conditions create strong currents in the southern sound.

Before the situation in Fig. 7, the wind has blown one hour from the opposite direction to the foregoing with a speed of 5 to 10 m/s. The changes in water levels are minor, some levelling out being observable, but in volume transport the backward motion is clear. The influence of the Coriolis force also appears as a turn of the water masses to the right.

Fig. 8 displays a case with a wind which has blown continuously for four more hours from the same direction, but with a speed of 5 to 15 m/s. The subsidence of water in the north east is rather high and the piling up moderate in spite of the southern sound, which clearly cannot transfer the large amount of water in the time available. Otherwise the water moves almost perpendicularly to the direction of the wind. This may be due to the presence of seiches.

The situation displayed in Fig. 9 is mainly caused by a south—south-west wind with a speed of 25 to 35 m/s blowing for the preceding three hours. Piling up is strong in the north-east of the area as is also subsidence in the south-west. Water transport to the north and north-east is also strong. Otherwise the situation greatly resembles that shown in Fig. 6.

5.1.2 Comparison of the computed water level with the observed one in two particular cases

Because of the specific nature of the wind used in the experiment, it seems impossible to find natural conditions which are directly comparable with the one treated. But cases with some features in common with the one in question may yet exist. Although the condition of correct wind speed and direction can hardly be fulfilled at the same time, it may still be possible to find a correct wind direction when allowance for different wind speed and duration is made.

In our model the wind blows in the lengthwise direction of the Gulf of Bothnia with a speed given in Fig. 5. The aim is to compare the tendencies (*i.e.* local time derivatives) of the computed water level elevations during the first three hours in the model with the tendencies observed in an actual case, and the calculations of the next three hours in the model with another observed case (see Fig. 11). To this end, the water elevations scale and the time scale in Fig. 11 are made proportional, so

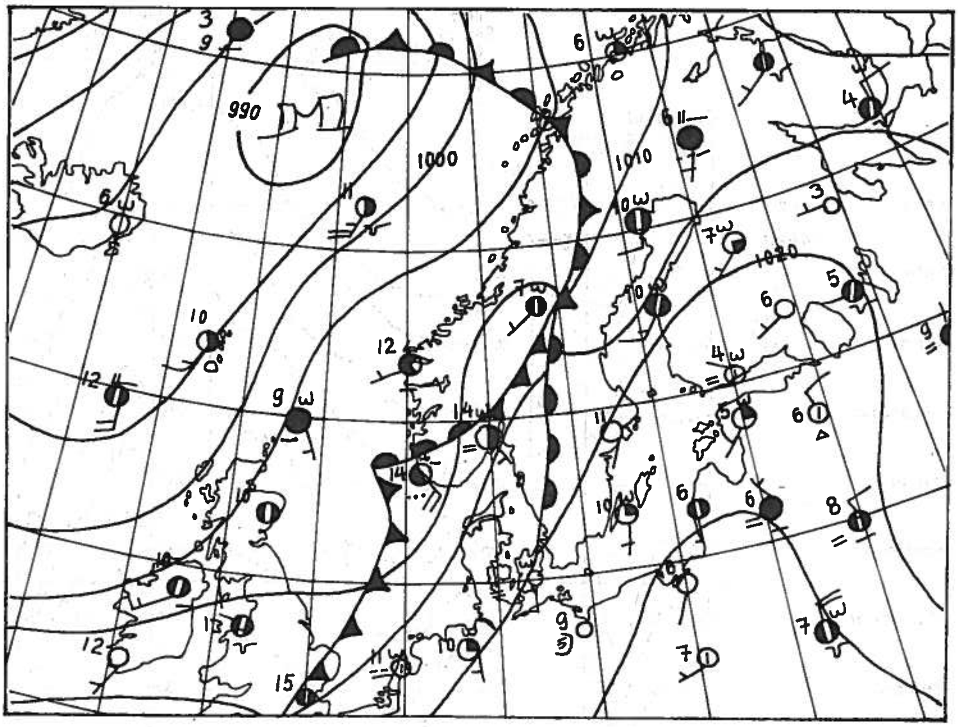

Fig. 10. Weather map for Sept. 16, 1965, at 8 o'clock.

that equal time derivatives will show equal tilting of the curve. The water elevations are given as tide gauge readings. Additional water elevation scales are provided to make the comparison easier.

As the observed case to be compared with the behaviour of the model during the first three hours, we have chosen the conditions of Sept. 15 and 16, 1965. The weather conditions on the morning of Sept. 16 can be seen from Fig. 10. The wind data concerned are reproduced in Table 4 *) and corresponding water level data in Fig. 11 **). The computed water elevations are also reproduced in Fig. 11 as linear extrapolations from nearby data.

For a few days before the one in question, the weather had been calm because of the prevailing high pressure. This was especially true of the north of the Bothnian

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*) All meteorological data published in this paper are collected from archives of the Finnish Meteorological Office, Helsinki, Finland.

**) Water level data from the Finnish tide gauge stations are collected from papers of the Institute of Marine Research, Helsinki, Finland, while data from the Swedish tide gauge stations are partly from copies of papers at the SMHI (Swedish Meteorological and Hydrological Institute, Stockholm) and partly from publications of the same institute (see Sveriges Meteorologiska och Hydrologiska Institut 1966).

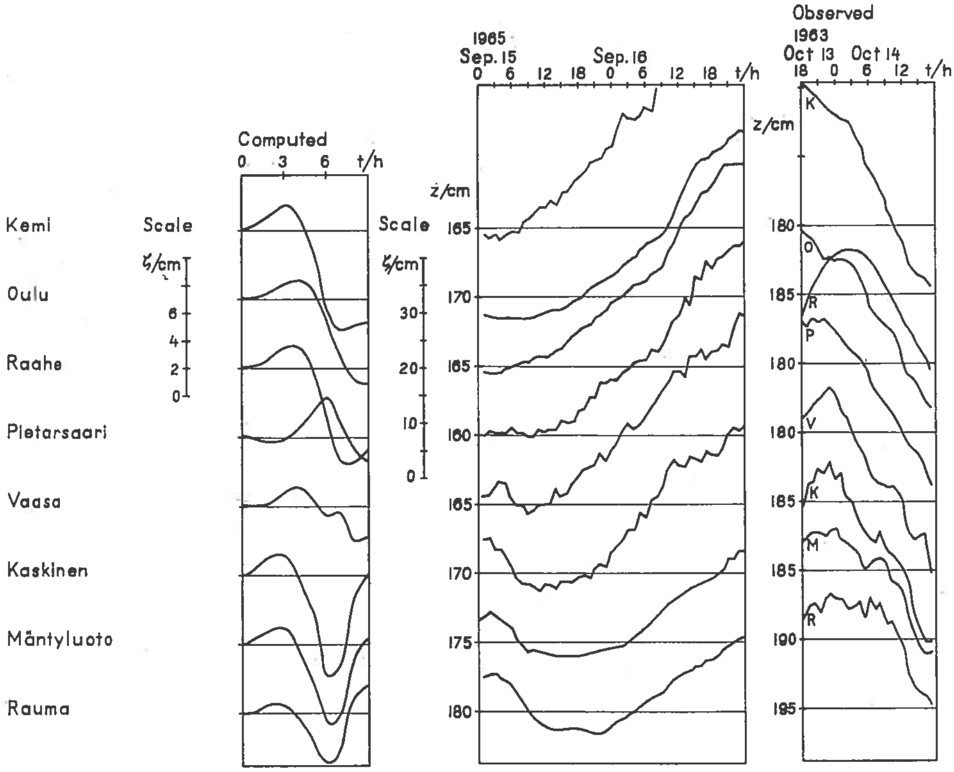

Fig. 11 a. Water levels at the tide gauges along the Finnish coast of the Gulf of Bothnia.

TABLE 4. Wind data for Sept. 15 and 16, 1965.

	Sept. 15								Sept. 16							
Station — t/h; $\varphi/10°$, $v/(\mathrm{ms^{-1}})$	2	5	8	11	14	17	20	23	2	5	8	11	14	17	20	23
Kemi	36	03	02	19	21	19	17	15	15	15	20	19	19	18	18	18
	01	01	02	01	01	04	01	02	03	03	04	06	06	07	04	03
Oulu	06	06		23	28	24	21	18	14	15	21	17	20	18	18	21
	01	02	00	02	04	05	03	04	05	04	04	06	06	06	05	03
Pietarsaari	05	05	05	10	22	22	22	21	21	21	19	19	20	22	22	22
	03	03	03	02	03	06	07	05	06	06	07	08	09	08	06	08
Vaasa	09	14	11	09	09	07	07	06	22	20	20	21	22	23	21	22
	02	02	04	06	05	04	05	05	04	03	08	06	06	06	07	07
Mäntyluoto	04	04	02	04	35	35	34	25	21	21	20	19	19	19	19	19
	02	03	05	03	05	08	03	03	03	07	09	12	13	13	13	14
Rauma		36	02	02	34	34	32			18	18	20	19	18	18	
		04	04	05	06	07	05			04	08	11	09	09	09	

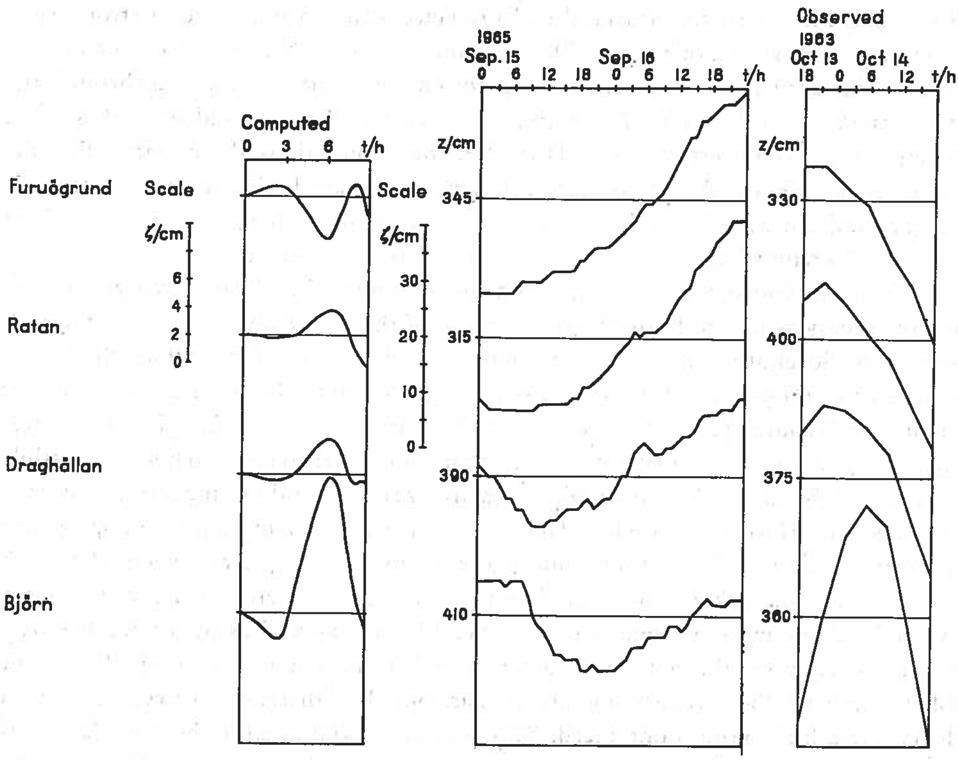

Fig. 11 b. Water levels at the tide gauges along the Swedish coast of the Gulf of Bothnia.

Bay and the waters there were well levelled out, but further to the south a weak wind had blown from the north-east causing some water level variations.

Let us first consider events in the Bothnian Bay. When the wind began to blow from the south-west, it took some time to reach its peak value, its speed increasing little by little. This condition doest not correspond to our experiment, but does not invalidate comparison, because the influence of a weak wind preceding the actual situation is relatively small and the counteraction of the piled up waters is still of minor importance. On the other hand, the friction against the bottom in shallow waters is relatively high and so the attenuation of the water motion is considerable. Therefore, the rates of change on the water levels at Furuögrund, Oulu and Raahe were only slightly larger than the calculated ones at a wind speed of 5 ms^{-1}. It may be mentioned that the inflow of waters through Merenkurkku over some length of time has a tendency to increase the water levels of the Bothnian Bay. However, at Kemi the water level increased at a faster pace than that calculated. This can be explained by assuming that the changing atmosperic pressure field generated a shallow wave, which, on arrival at the northern coast, caused the piling up of waters there. At

Ratan and Pietarsaari the observed and predicted values seem to be in strong contrast. Yet there is an explanation. During wind pulses of short duration, such as the one in our calculations, the waters have not enough time to penetrate through the narrows of Merenkurkku. Therefore, it is natural that a subsidence takes place owing to the southwesterly blast. However, the observations show that at first the water level remained almost constant with a changing wind. This means that the rate of the wind did not change fast enough to create a subsidence. Later on the inflow through Merenkurkku exceeded the outflow to the north-east.

On the Bothnian Sea the comparison of the observed and calculated water level is not so easy as on the Bothnian Bay because of the rather unnatural assumption of zero water level at the southern sea boundary and because of the wind, which only reached the proper direction after some time. At Vaasa the wind direction at first rotated unfavourably, but then settled in the correct direction. In spite of the prehistory of the current, the rate of change of the water levels seems too high. A possible reason may be that real wind speeds at sea are greater than those measured at coastal stations. For Kaskinen no wind data are available. At Mäntyluoto an appropriate wind only prevailed for a short while, but a comparison of the tide gauge data with the calculated ones shows that their fit is plausible. The influence of the sea boundary water level assumptions begins to be noticeable here as well as in the Rauma area, where in addition the wind was possibly rather unsuitable for comparison. The phenomena on the Swedish side are similar, but the differences between the water levels are a little more pronounced. This is quite natural because the boundary condition of zero water level was also used for the sound on the south of the sea. This caused the high water transport values there.

Most of the remarks concerning the comparison of the calculated water elevations for the first three hours with a real case also apply when the water level calculations

TABLE 5. Wind data for Oct. 13 and 14, 1963.

Station	t/h $\varphi/10°$ $v/(\mathrm{ms}^{-1})$	Oct. 13 20	23	Oct. 14 2	5	8	11	14	17	20
Kemi		07	05	05	04	05	02	01	31	00
		04	04	05	05	07	06	06	04	00
Oulu		14	14	12	09	06	05	05	06	36
		03	03	02	02	03	04	04	02	05
Vaasa		08	08	06	06	04	05	05	02	01
		02	04	05	04	06	07	08	06	04
Mäntyluoto		12	10	07	07	03	02	02	02	01
		06	05	09	11	09	10	11	11	09
Rauma		08			04	03	02	02	36	35
		06			09	08	09	08	08	08

of the next three hours are compared with the conditions of another observed case, *viz.* those of Oct. 13 and 14, 1963. The wind data are collected in Table 5 and the tide gauge data in Fig. 11. The initial water movement water conditions are not the same as in our experiment, but since the influence of the past smooths out fairly fast, it may still be possible to compare the events. Some care must naturally be exercised because the observed water level at the begin of the comparison is rather high and a tendency to seiches is evident. The wind speed in our experiment varied from 5 to 15 m/s, and was thus 10 m/s on an average. This high wind was observed at Mäntyluoto only and there the agreement of the water level variations with the calculated ones is satisfactory.

5.2 MOTION OF INDIVIDUAL PARTICLES

Originally, this work was planned to investigate the rotational state of waters in the Gulf of Bothnia under different meteorological conditions and, the examination of subjects of this kind is consequently included here.

It is well known that the currents in closed sea basins are generally counter-clockwise (see *e.g.* Palmén, 1930). Also the primary driving force, the wind, has on an average a curl component of the same sign. But, can a wind without any curl whatsoever generate currents which have mean curls different from zero?

If the motion of single water particles is considered, it can be noted that the speed of a particle in the vicinity of a grid can be approximated by

$$\frac{dx_0}{dt} = u_0 \tag{5.1}$$

$$\frac{dy_0}{dt} = v_0 \tag{5.2}$$

where x_0, y_0 are Cartesian coordinates of the water particle situated at P at the beginning of the observations and u_0, v_0 the corresponding velocity components. These are the averaged velocities from the bottom to the surface. They have been found by dividing the calculated volume transports by the corresponding depths. The actual velocities are not known. Therefore this method can yield only fictitious movements of water particles. Otherwise the approximation is rather good if the total movements of particles remain below certain limits, a few kilometres, say.

The solution of (5.1), (5.2) is

$$x_0 = \int_0^t u_0 dt$$

$$y_0 = \int_0^t v_0 dt.$$

The calculations were performed at 14 selected points. In Fig. 12 they are indicated by dots, which form the particle orbits. The numbers nearby give the time (in hours) from the beginning of the experiment. In order to reveal the forms of the orbits more clearly, they are drawn in another scale from that of the map itself. The crosses indicate the initial positions of the particles in question. The initial part of the curve is very difficult to distinguish because of the low wind speed used at the start of the experiment. It can be observed that the orbits are spirals, which open in a haphazard manner in the Bothnian Bay and Merenkurkku, whereas in the Bothnian Sea the curvature of the trajectories is cyclonic.

5.3 MEAN VORTICITY

To obtain a better view of the rotational state revealed by the motion of individual particles, vorticities were examined in both the Bothnian Bay and the Bothnian Sea. To this end, loops were devised in both areas (see Fig. 3). These loops were drawn as near the coastlines as possible, while taking care to avoid the disturbances caused by the coast. Furthermore, the loops were planned to be simple and yet to traverse as many grid points as possible to avoid unnecessary interpolations. The mean vorticity of the volume transport is found separately for each sea area by

$$\psi = \frac{C}{A} = \frac{1}{A} \int_{L} (Udx + Vdy), \tag{5.3}$$

where C is the corresponding circulation and A the area of the loop L in question. A numerical approximation of (5.3) was found by performing the integration over distances determined by the grid points along the integration path. The individual integrals were then approximated by the trapezoid rule. The calculated vorticity in the Bothnian Bay and the Bothnian Sea is plotted as a function of time in Fig. 13. It is observed that the oscillations in the Bothnian Bay are more irregular than those in the Bothnian Sea. This is in agreement with the fact that the curvature in the Bothnian Bay is cyclonic at certain points and anticyclonic at others, while the curvature in the Bothnian Sea is always cyclonic.

5.4 TIDE-LIKE PHENOMENA

Some phenomena in our experiment have a close resemblance to tides. In Fig. 14 a number of lines of steepest ascent (*i.e.* lines which are perpendicular to lines of the same water levels, the isohypses) resembling cotidal lines have been drawn. Almost in the centre of the Bothnian Sea is a point corresponding to an amphidromic point. This point was found by drawing zero water levels for each hour calculated. These

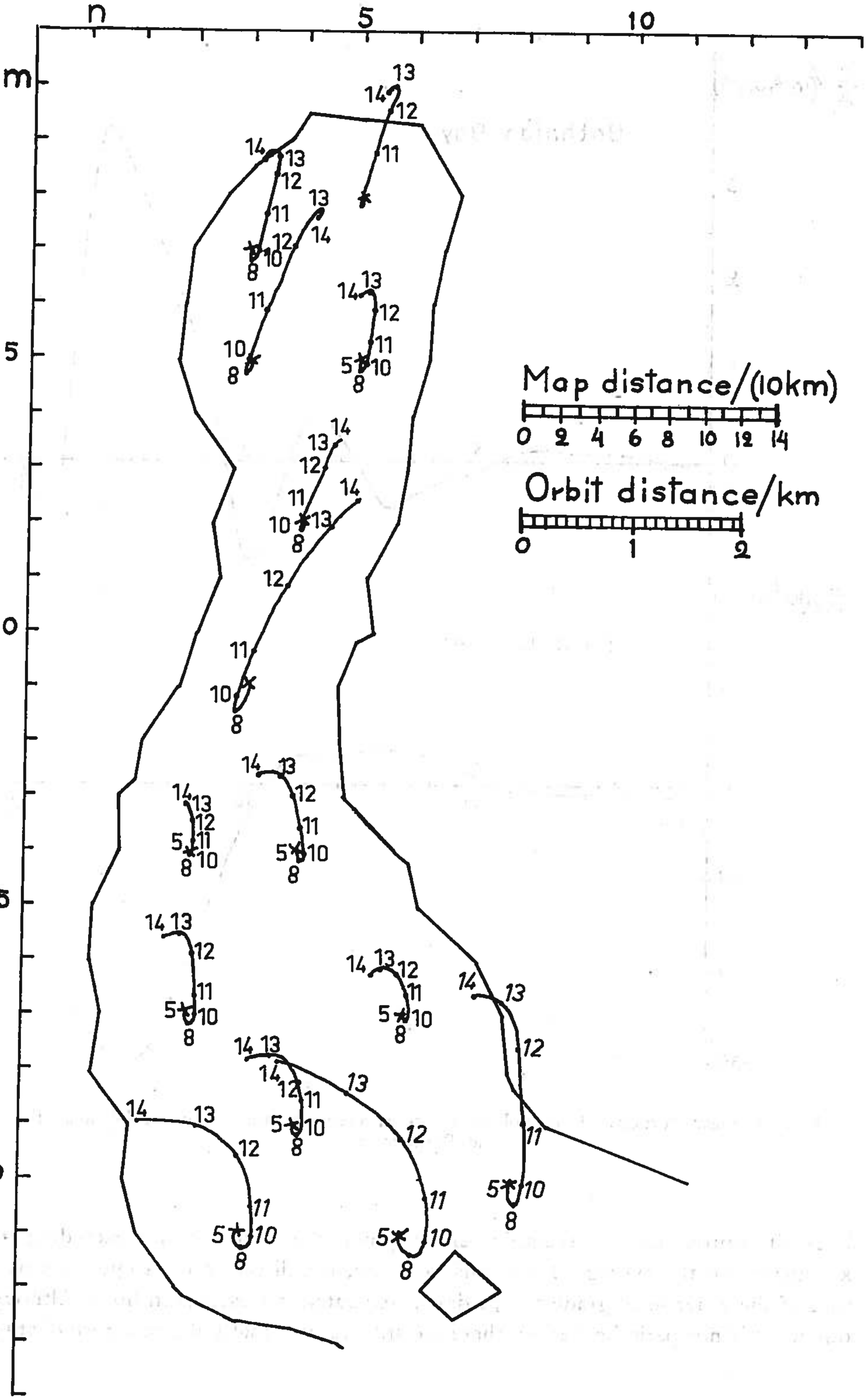

Fig. 12. Orbits of water particles which have started from points denoted by crosses at the beginning of the experiment. The orbits and the map are drawn on different scales. The numbers show the time (in hours) from the beginning of the experiment.

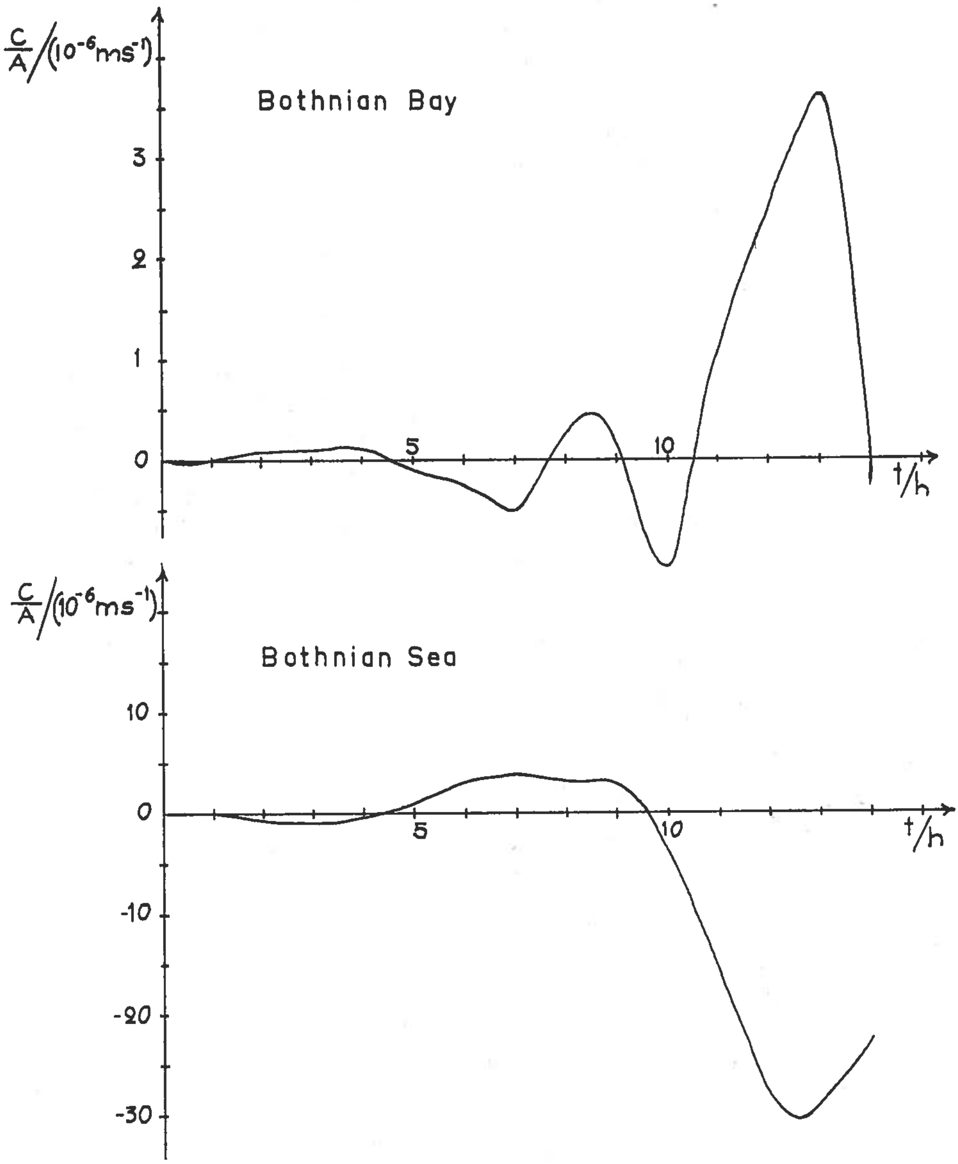

Fig. 13. Mean vorticity of the volume transport shown separately for the Bothnian Bay and Bothnian Sea.

lines all approximately traversed a single point, the deviation not exceeding five kilometres on the average. From this point on, the direction of steepest ascent or that of the water level gradient was drawn separately for each even hour. Although our wind is not periodical at all, there are still features that indicate a periodicity of

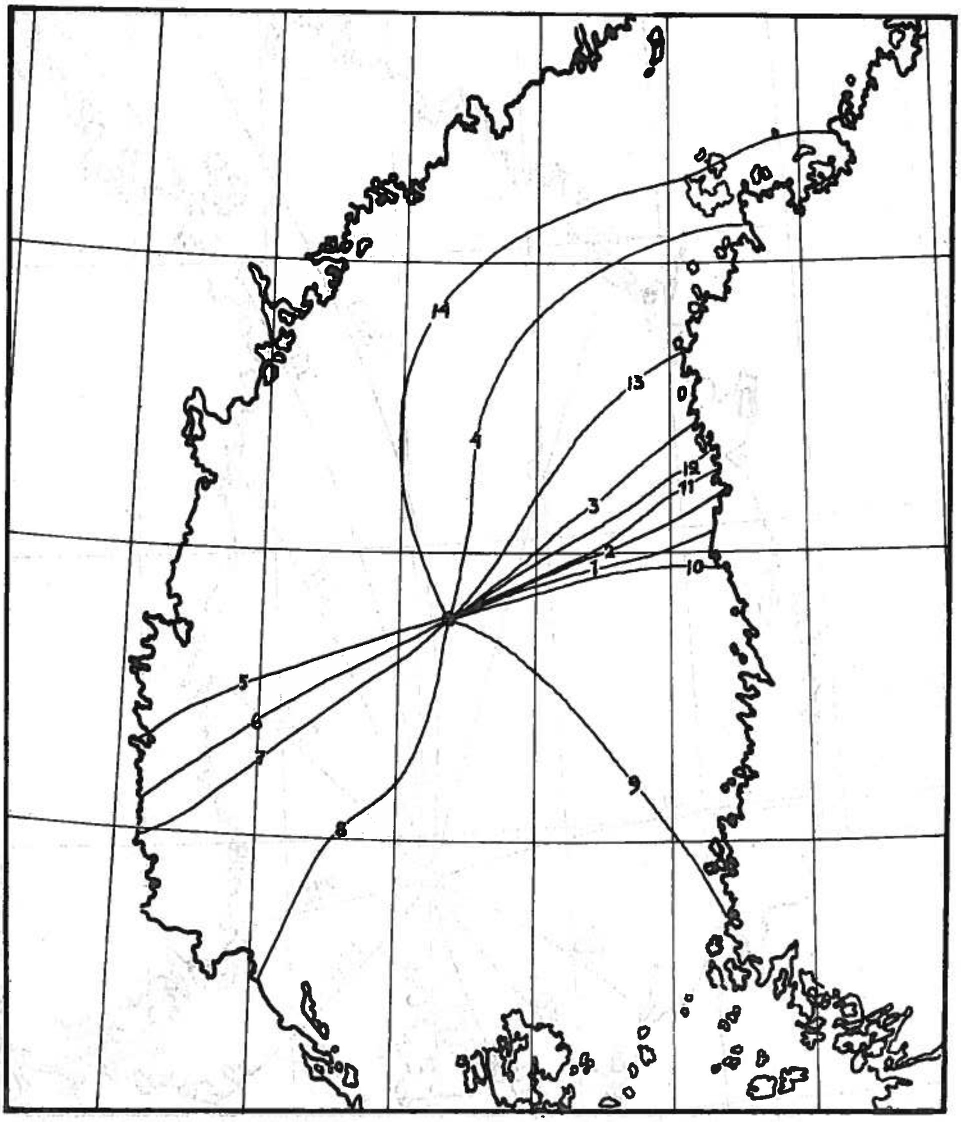

Fig. 14. Lines of steepest ascent of the computed water level. Only maximum branches are represented. The numbers show the time (in hours) from the beginning of the experiment.

12 hours. Therefore our tide-like phenomena can be compared with of the M_2-tide for which the period is 12 hr 25 min. Defant (1961) has determined the location of an amphidromic point for the M_2-tide, but it is situated some 115 km to the south of our corresponding point (*cf.* Fig. 15).

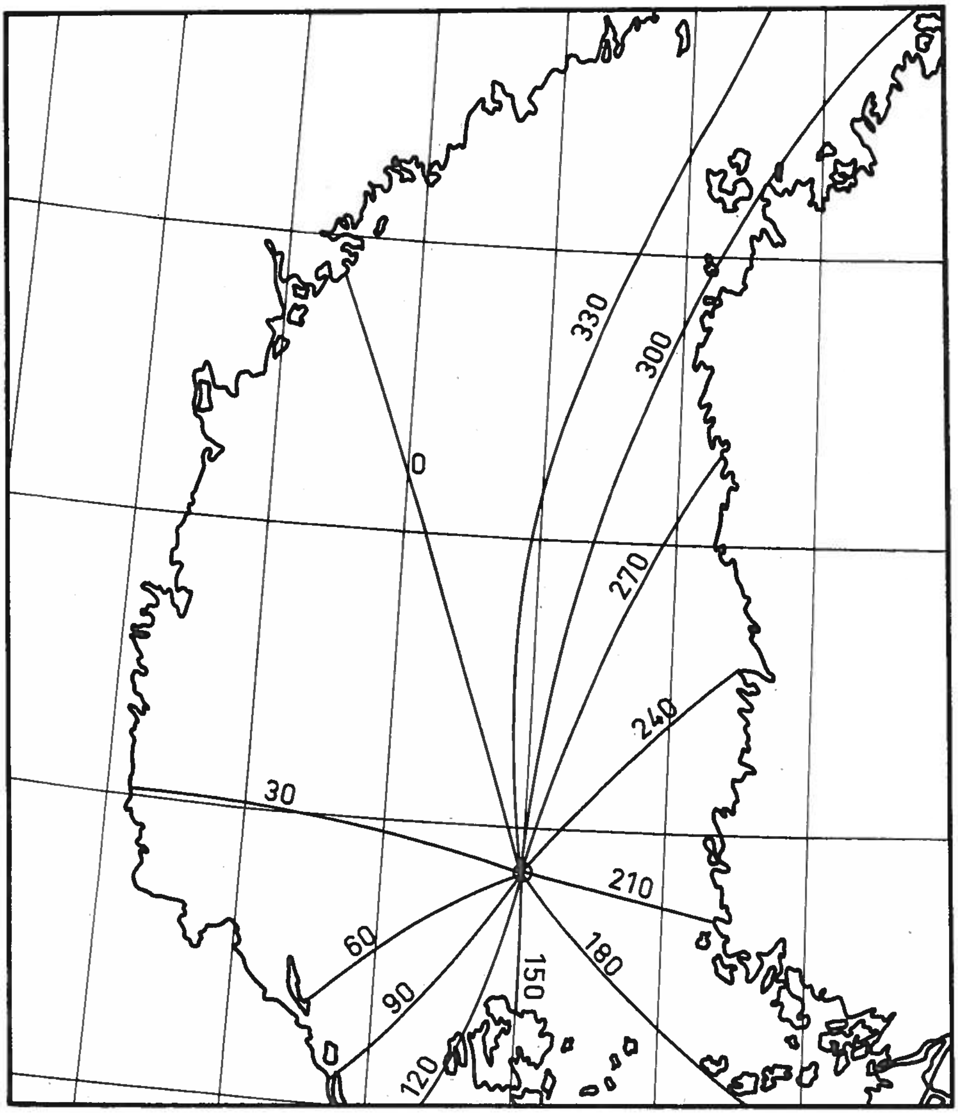

Fig. 15. Cotidal lines and amphidromic points in the Baltic Sea for the M_2-tide (according to Defant, 1961).

6. CONCLUSIONS

According to the present calculations, the model constructed seems to be capable of reproducing the behaviour of waters in the Gulf of Bothnia. A comparison of water levels in some observed cases with the computed values gives satisfactory results. The motion of water particles calculated in the model is natural. The model is also capable of displaying some tide-like phenomena. Thus, it seems that it can be used for at least rough calculations of volume transport and water level variations in the Gulf of Bothnia. A more accurate analysis of the reliability and performance of the model remains to be made by making calculations with a realistic forcing function and comparing the results with observed conditions.

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