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International Council for the Exploration of the Sea, ICES

C.M. 1987/C:39
Hydrography Committee

LONG TERM AND SEASONAL WATER QUALITY MODELLING OF THE NORTH SEA AND ITS COASTAL WATERS

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Abstract

The long term mean global circulation pattern in the North Sea is estimated with three nested two-dimensional vertically integrated tidal hydrodynamic models with increasing spatial detail. The residual flow field is derived by averaging over the tidal cycle. This flow field has been used to determine the transport patterns of influxes in the North Sea and to estimate the "age" of the influxes in the North Sea under average conditions.
These ages may amount up to a year and over. This suggests that for substances a long term global concentration pattern exist around which the individual situations are grouped according to the actual wind and tides. The long term global salinity pattern determined this way bears a good resemblance with inventories of measured data for the North Sea as a whole. Although this model setup is not suited for a description of the near field outflow phenomena of Rhine water in the North Sea, the concentrations somewhat further from the outflow are reproduced reasonably, especially where they form the southern boundary condition of the German Bight.
A comparison of the mean winter and summer salinity concentration in front of the Dutch coast does not show great differences. This is probably due to the fact that the lower summer mean inflow for the river Rhine compensates the slower circulation pattern in the North Sea. For nitrogen the effect of seasonal variation in loads and non-conservative behavior is assessed. For cadmium a waste-load scenario is evaluated.

This study demonstrates the potentials of long term global waterquality modelling and indicates the type of data needed for verification of these models especially if seasonal fluctuations and non conservative behavior are involved.

Introduction

The North Sea is surrounded by highly urbanized and industrialized countries. As result it is intensively used for a manifold of purposes such as fishery, shipping, recreation, nature conservancy, mining and dumping activities. Furthermore the North Sea receives inputs of contaminants from various sources. This combination constitutes a stress on the North Sea, the effect of which is observed by many scientists as concentration levels of substances and behavior of the ecosystem.

The inputs of wasteloads are among the few manageable parameters of the North Sea ecosystem. So it is of utmost importance to determine the relation between the inputs and concentration levels and effects to direct the quality management of the North Sea (Rijkswaterstaat, 1985). Mathematical modelling techniques contribute to the insight into this relation. They also enable an assessment of the effects of sanitation strategies.

In this study the main attention is given to the model instruments for the derivation of global long term concentration patterns of substances and seasonal characteristics. The availability of consistent sets of data for larger parts of the area and for different seasons are of crucial importance for the identification of microbiological and chemical processes, as well as for their calibration and verification.

The use of hydrodynamic information is limited to the tidally averaged residual flow field, to produce an estimate of the long term global dispersion patterns of influxes. This study shows the results that can be obtained already with such relatively simple assumptions. A step towards representation of a specific sequence of global concentration patterns may consist of the incorporation of the variability of winds and influxes. For the nutrient cycles and primary production, however, the effect of processes is estimated to be at least as important as the time dependencies of flow.

Hydrodynamic circulation

The transport pattern of pollutants in the North Sea is largely determined by the global movement of water bodies in the area. To assess this movement, a set of three hydrodynamic models has been used, all departing from the depth averaged shallow water equations, using an implicit alternating direction scheme (Stelling 1984).

The area covered by the models is depicted in figure 1. The largest model covers the whole of the continental shelf around England in order to minimize wind effects on the boundary conditions. It received boundary conditions from the model of the Atlantic Ocean of IOS at Bidston. It is only used as a generator of time dependent boundary conditions for the two inner models (Verboom et al 1986).

The second model covers the North Sea with a grid of computational elements of 8 km x 8 km and is called the "overall model" in this contribution. The third model covers the southern part of the North Sea with much more detail and is called the "detail" model in this contribution. The computational elements have a size of 3200 m x 3200 m.

The tidal flow has been determined according to cyclical tidal boundary conditions, wind forces, bottom roughness and coriolis forces. The models were accurately calibrated for tidal velocities and water levels (Voogt, 1984).

The tidal flows as determined by the models were averaged over the tidal cycle, to obtain a residual flow pattern. For this study over ten fourier coefficients of the waterlevels of an average tidal cycle have been used as boundary condition.

The wind directions and velocities observed hourly during a 30 year period at the light vessels Noordhinder an Texel have been analyzed to obtain a wind direction and velocity corresponding with the average windstress during this period (Visser, 1987). This resulting velocity of 4.5 m/s from the South West has been applied for the whole model. Figure 2 shows the frequency of the wind directions and the velocity from these directions averaged on a wind stress basis for both the winter and summer period. It turns out that the average direction does not differ much only velocities are lower in summer as an average.

In figure 3[a] the streamlines of this residual flow pattern as determined with the overall model are given with a 25.000 m^3/sec interval. Figure 3[b] shows the sensitivity of this pattern if a wind of 3.5 m/s from the NW would prevail. The direction field of the residual flow as determined with the detail model is given in figure 4.
Both figures show a counter clockwise circulation pattern around a stagnant zone near Doggersbank. Similar patterns were already suggested in 1922 (Böhnecke, 1922), (see also Eisma, 1986).

Transport of substances

To assess the transport of substances in the North Sea, a transport model is used, based on the vertically averaged advection diffusion equation. The same grid spacing is applied as for the corresponding hydrodynamical models. The equation is solved with an implicit central difference scheme which has no numerical diffusion up to the second order. Figures 5 and 6 show the model area and the main river inputs as distinguished in the model.

The steady residual transport velocity field, calculated by the hydrodynamical models; is used as advective term in the transport model. A mixing term accounts for the combined effects of the varying wind stress fields, the averaging over the tidal cycle and over the vertical and for turbulent diffusion. This dispersion coefficient has been calibrated roughly to reproduce the global salinity patterns as given by ICES (1962) (figure 7). An uniform value of 150 m^2/s for the overall model and 120 m^2/s for the detail model provided acceptable results (figure 8).

In the detail model a much larger dispersion coefficient is used in the outflow regions of the Rhine and the Scheldt to represent the southward spreading of river water against the mean flow direction. This phenomena is observed in the mean-summer and mean-winter salinity patterns (see figure 9). The data in front of the Dutch coast originate from the bi-weekly sampling campaign of the Dutch Rijkswaterstaat at 76 locations during the years 1975-1983. For seasonal interpretation, they have been averaged over the 7 month of april-october to obtain a long term summer mean and over november-march to obtain a long term winter mean (Rijkswaterstaat '75-'83).

A comparison of the model results with the measurements show a reasonable agreement with only minor differences between the summer and winter means.

With this model, the transport of the continuous inflow of river water from the different sources is determined, together with the "age" of the river water.

The "age" of the river water is defined with the help of the model solution of the first order decay equation.

$$C = C \cdot \exp(-kt)$$

giving

$$t = \frac{1}{K} \log\left(\frac{C_o}{C_t}\right)$$

with C_o and C_t representing the concentration at time = o and t respectively, K is a small decay coefficient and t is time.

In figures 10 and 11 the percentage of the water column originating from the Thames and the Rhine are depicted together with the "age" of the water. They illustrate the fact that water from the English coast crosses the North Sea, whereas the Rhine water remains concentrated in the eastern coastal areas. Both figures also illustrate the travel time of the Thames and Rhine water in the North Sea, being several hundreds days.

The same figures have been drawn for all other influxes in the area and are compiled to a Transport Atlas for the Southern North Sea, together with a display programme for concentrations running on a personal computer (De Ruijter et al, 1987).

Pollution inputs

An inventory was made of the annual pollutant loads entering the North Sea between the Strait of Dover and 56°N, based on the situation in 1980. The data on pollutant loads from coastal zones are primarily based on ICES (1978), updated with recent information from the Governmental contributions to the 1984 North Sea Ministerial Conference in Bremen (Carlson, 1986). Estimates of atmospheric deposition are based on observations at land sites close to the North Sea. As these data show a wide range of deposition rates, their average has been derived and applied for the whole area under consideration. Cross boundary inputs from the Channel and the North Atlantic are calculated from measured concentrations and inflows of water masses as quantified by hydrodynamic modelling.

Table 1 gives an overview of land based pollution inputs.
This table illustrated the high input from the Dutch coast, especially by the Rotterdam Waterway and the Haringvliet sluices being the main discharges for the rivers Rhine and Meuse. It's undeniable that the total input from the Dutch coast reaches above the input from other bordering countries. However, a large part of this input originates from upstream countries like W. Germany, France, Switzerland and Belgium.

The input from the German coast is dominated by the river Elbe discharge. Similar to the river Rhine this Elbe input also originates from upstream countries, in this case the GDR.
The input from the UK is dominated by the input from outfalls and sludge dumping, represented by the group of various inputs in Table 1.
Also the rivers Humber and Thames represent a large part of the total input from the English coast.
It must be stressed that the inputs considered in Table 1 are restricted to the 1980 inputs into the North Sea between the Strait of Dover and 56°, Other inputs, like the land-based inputs from the southern coast of the UK, from France and from Scotland are not considered separately. As such they are assumed to be represented in the quality of the cross boundary inflows into the region considered.

Source	Flow km^3/y	Susp.sol 1000 t/y	N 1000 t/y	P 1000 t/y	Hg t/y	Cd t/y	Pb t/y	Cu t/y	Cr t/y	Zn t/y
UK										
Forth	2.0	55	0.8	0.20	0.54	1.5	29.0	30.0	17.5	72.5
Tees	0.5	13	1.8	0.22	0.16	0.6	12.5	10.0	8.0	56.0
Tyne	1.6	12	0.9	0.19	0.43	1.5	26.5	26.5	17.5	199.0
Humber	8.8	123	43.5	0.57	2.36	8.6	132.0	162.0	100.0	470.0
Wash	1.5	7	17.7	1.14	0.43	1.6	50.0	44.0	48.0	175.0
Thames	4.9	188	32.8	0.11	1.29	2.2	16.5	16.5	15.0	72.0
var.inp	-	4292	98.5	25.6	15.0	32.4	839.5	863	489	3104
Belgium										
IJzer	0.2	16	0.3	0.24	0.05		1.0	1.0	1.0	5.0
Oostende	0.5	50	4.5	0.71	0.07	0.2	2.0	3.0	2.0	25.0
var.inp	-	-	2.2	0.25	0.98		243	1.0	1.0	101
Netherlands										
Scheldt	3.8	400	42.5	5.5	1.5	12.0	120.0	70.0	120.0	500.0
E. Scheldt	2.1	50	2.9	0.21	0.1	0.4	1.0	2.0	2.0	4.0
Haringvl. Sl	28.4	320	120.0	12.0	3.7	23.0	100.0	145.0	115.0	1200.0
R. Waterway	48.0	1000	260.0	34.0	3.8	43.0	340.0	480.0	630.0	2800.0
Oude Rijn	0.3		2.0	0.4		0.2	3.0	4.0	2.0	9.0
N.Z. kanaal	2.6	60	17.9	2.3	0.7	1.5	97.0	21.0	26.0	490.0
Den Oever	9.0	180	34.0	2.1	0.72	2.1	44.0	33.0	39.0	246.0
Kornwerd.	6.0	120	28.0	1.6	0.5	1.2	29.0	28.0	26.0	174.0
Lauwersz.	1.4	25	5.2	0.9	0.14	2.0	21.0	17.0	7.0	67.0
Ems	3.3	70	35.0	3.1	0.76	3.4	20.4	51.5	13.0	95.0
var.inp.	5.1	1578	35.5	10.4	9.0	46.0	389.6	273.5	543	3042
W. Germany										
Weser	15.8	340	42.0	8.6	1.18	4.7	83.4	191.0	54.0	1655.0
Elbe	36.2	800	250.0	14.0	7.5	15.0	135.0	300.0	200.0	2500.0
var.inp.		217	17.0	2.5	0.42	1.0	25.6	221	12	273
Denmark	2.5	50	4	0.3		3.6	32.0	21.0	21.0	140.0
Total	182	9916	1105	127	51.2	208	2793	2943	2509	16480

Table 1 Pollution inputs into the North Sea between the Strait of Dover and 56°N. by rivers, outfalls and dumping (1980)

In order to enable a comparison between the coastal zone inputs and other inputs like cross boundary inputs and atmospheric deposition a summarize over view of these data is presented in Table 2.

From a review of "natural" river concentrations (Van Eck, 1983) an estimate was made for non-polluted river inputs. Based on this information the total land-based reference input was derived and compared with the total 1980 input into the considered part of the North Sea.
The difference between the 1980 and reference input is defined as the anthropogenic fraction.
Table 2 shows that the so defined anthropogenic influence reaches between 25-50% for the considered nutrients and heavy metals.
As this percentage represents the average influence for this part of the North Sea, the influence will regionally be higher (see Section 5).

Sources of pollution	Flow km^3/y	N 1000 t/y	P 1000 t/y	Cd t/y	Hg t/y	Pb t/y	Cu t/y	Cr t/y	Zn t/y
Coastal inputs:									
United Kingdom	19	196	28	48.4	20.2	1106	1152	695	4152
Belgium	0.6	7	1.2	0.1	1.1	246	5	4	131
Netherlands	110	583	72.5	134.8	20.9	1165	1125	1523	7629
W. Germany	52	309	25.1	20.7	9.1	244	640	266	4428
Denmark	-	10	0.3	3.6	-	32	21	21	140
Total (1980)	182	1105	127	208	51.2	2793	2943	2509	16480
Total (reference)	(182)	(273)	(18.2)	(12.7)	(7.3)	(619)	(510)	(546)	(2548)
Atmosphere		220	10	66	8.8	2420	1320	66	8806
Channel	4786	957	120	129	15.8	813	1914	3254	3493
N.Atlantic O.	5899	767	112	147	15.9	295	1652	2242	2537
Total (1980)	10867	3049	369	550	91.7	6321	7829	8071	31316
Total (reference)		(2217)	(260)	(355)	(47.8)	(4147)	(5396)	(6108)	(17384)
Anthropogenic fract.		27%	30%	35%	48%	34%	31%	24%	44%

Table 2 Overview of sources in the southern part of the North Sea (area 219900 km^2) and an estimate of the anthropogenic fraction, 1980

It should be noticed that the anthropogenic contribution by atmospheric deposition and cross boundary inflows is not considered. The anthropogenic influence in the total input therefore represent a lower limit.

Concentration patterns

The mathematical models can be used to estimate the concentration patterns in the North Sea. A first assessment is obtained by using the river inflows and other sources of substances and input and by considering the substances as non-reacting.

In the following, model predictions of some concentration levels will be compared with measured concentrations as derived from literature and with measured concentrations in front of the Dutch coast. As hardly any comparative information is available on the seasonal characteristics of the wasteloads in different countries, yearly average values are used in most other cases.

- total Nitrogen

For total-Nitrogen separate values for the summer and winter mean concentrations have been used for the Scheldt and the Rhine and for the southern and northern boundaries, according to table 3. For the other inputs the values of tables 1 and 2 have been used.

source	Winter	Summer
Rhine	7.0	5.0
Scheldt	14.5	10.0
North Atlantic Water	0.13	0.09
English Channel Water	0.18	0.09

Table 3 Seasonal model input for Total-Nitrogen in mg/l.

The precise spatial concentration patterns near the outflows of the Rhine and Scheldt cannot be predicted well with this type of models. This is mainly because the effect of the vertical salinity gradients on the patterns of outflow, as well as the wind induced and tidal currents in front of the outflows, are lumped in an uniform dispersion coefficient for the area. If, however, some distance away from the vicinity of the outflows a good agreement can be noticed, the influence of the outflows on the North Sea as a whole is described well.

Model simulations as shown in figure 12 compare reasonably well with the figures of the seasonal averages along the Dutch coast (figure 13). This indicates that the total-Nitrogen concentration behaves almost conservative. This is the case if the bottom-fluxes compensate each other.

- Nitrate

Within the total-Nitrogen, however, the processes and mainly uptake by algae may shift the composition from the soluble from to the organic-particulate form. This is illustrated by two regression lines of Nitrate nitrogen with Chloride (figure 14). They are compiled from the summer and winter average concentrations of the subset of 53 stations in the Rhine outflow plume only. The straight line in winter indicates a conservative behavior. In summer the concentrations deviate from a straight line, indicating an uptake effect for intermediate salinities until the low levels in open sea become limiting for algal growth.

To model Nitrate only, one has to make an estimate of the Nitrate content of wasteloads. It is estimated at 60% of the total-Nitrogen loads of table 1 as a yearly average. For the Rhine, Scheldt, North Atlantic and English Channel the seasonal values of table 4 have been used.

Source	Winter	Summer
Rhine	4.5	2.9
Scheldt	7.0	4.2
North Atlantic Water	.08	.008
English Channel Water	.08	.008

Table 4 Seasonal model input for Nitrate in mg/l.

The results (fig. 15) show reasonable agreement in front of the Dutch coast for the Winter situation. For the summer situation, very low concentrations have been applied for the open boundaries and they produce even to high off-shore concentrations in front of the Dutch coast. This illustrates the removal process within the area that has caused a shift from nitrate to other forms of nitrogen. Comparison with the winter results of Johnston, 1973 as mentioned by Gerlach (1987), also shows good agreement for the coastal areas and even near the Doggersbank (figure 17). This comparison shows, however also that the measured winter boundary concentrations were higher than those applied in the model, but that they propagate only slowly into the area. The lower values in the center parts of the model area are most likely remnants of the low summer values.

The general conclusion that can be drawn from this is that it is necessary to have at least a consistent pattern of the main nitrogen fractions in the area for different seasonal situations within a year together with summer and winter chlorophyll, temperature and extinction values, to be able to calibrate and verify models of the nitrogen cycle for the North Sea.

- Cadmium

The loads as mentioned in tables 1 and 2 for Cadmium has been used as model input for the 1980 situation. If the transport to and from the bottom compensates, Cadmium can be treated as conservative substance. Figure 18[a] shows the result of this 1980 simulation. Data for verification of this type of modelling is hard to find. Duinker (1985) gives data for dissolved Cadmium (figure 19). With the assumption that 70% of the total Cadmium loads remains dissolved and with dissolved inputs of 0.0015 µg/l from the English Channel and 0.010 µg/l from the North Atlantic a reasonable agreement is produced with the model (figure 20). The construction of a storage reservoir for dredge spoil by the city of Rotterdam has reduced the amount of Cadmium loads from the river Rhine catchment area considerably. The model results for 1985 (figure 18[b]) show the effect on the concentrations in the sea.

Acknowledgement

the authors wish to thank Mr. P.J.A. Baan, Mr. F.C. van Stralen and Mrs. J.C. Beerstecher for their kind contribution to this study.

References

Böhnecke, G. (1922)
Salzgehalt und Strömungen der Nordsee
Inst. Meereskunde, Berlin, A 10

Carlson, H. (1986)
Quality status of the North Sea
International Conference on the Protection of the North Sea, Bremen, 1984
Dt. hydrogr. Z., Erg. - H.B., nr 16

Duinker, J.C., R.F. Nolting (1985)
Contaminanten in de Waddenzee
Final report M201 for the Ministry of Public Health and Environment (VROM)
Unpublished report (in Dutch)

Eck, B. van, E. Turkstra, H. van 't Sant (1983)
Voorstel referentie waarden Nederlandse zoute wateren
Ministry of VROM, Leischendam (in Dutch)

Eisma (1986)
The North Sea, an overview, Proceedings of the 2nd North Sea Seminar '86, Rotterdam
Werkgroep Noordzee, 1987

Gerlach, S.A. (1987)
Nutrients - An overview, International Conference on Environmental Protection of the North Sea (in Press)

ICES (1962)
Mear monthly temperature and salinity of the surface layer of the North Sea and adjacent waters, 1905 - 1954
ICES, Copenhagen, 1962

ICES (1978)
Input of pollutants to the Oslo Commission area, International Council for the exploration of the Sea
Cooperative Research Report No 77

Ruyter, W.P.M., L. Postma, J.M. de Kok (1987)
Transport Atlas of the Southern North Sea, Rijkswaterstaat - Delft Hydraulics, Delft, Netherlands, 1987

Rijkswaterstaat (1985)
Waterquality management plan North Sea
English edition, The Hague 1986

Rijkswaterstaat '73 - '83
Quarterly reports on the water quality in Dutch State waters
Rijkswaterstaat, The Hague (in Dutch)

Verboom, G.K., R.P. van Dijk, J.C.M. Dijkzeul
A fine grid tidal flow and storm surge model of the North Sea
IAHR - meeting, Taiwan 1986

Visser, D. (1987)
Analysis of wind measurements at the light vessels Noordhinder and Texel over the period 1951-1981
University of Utrecht, Institute of Meteorology and Oceanography, report IMOU 87-3

Voogt, L.
A tidal model of the North Sea based an JONSDAP 1976 data
Rijkswaterstaat report WWKZ-84 (in Dutch)

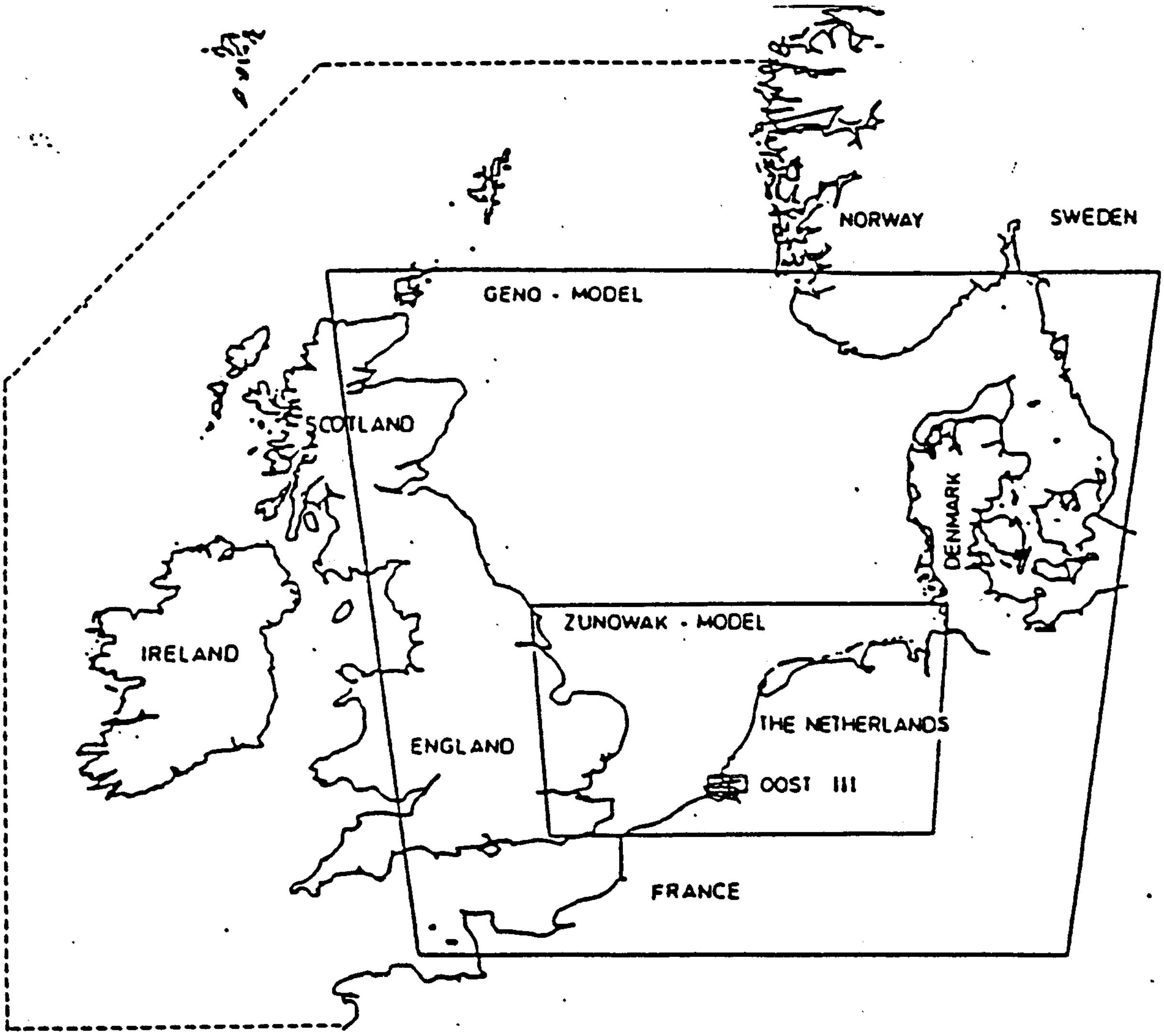
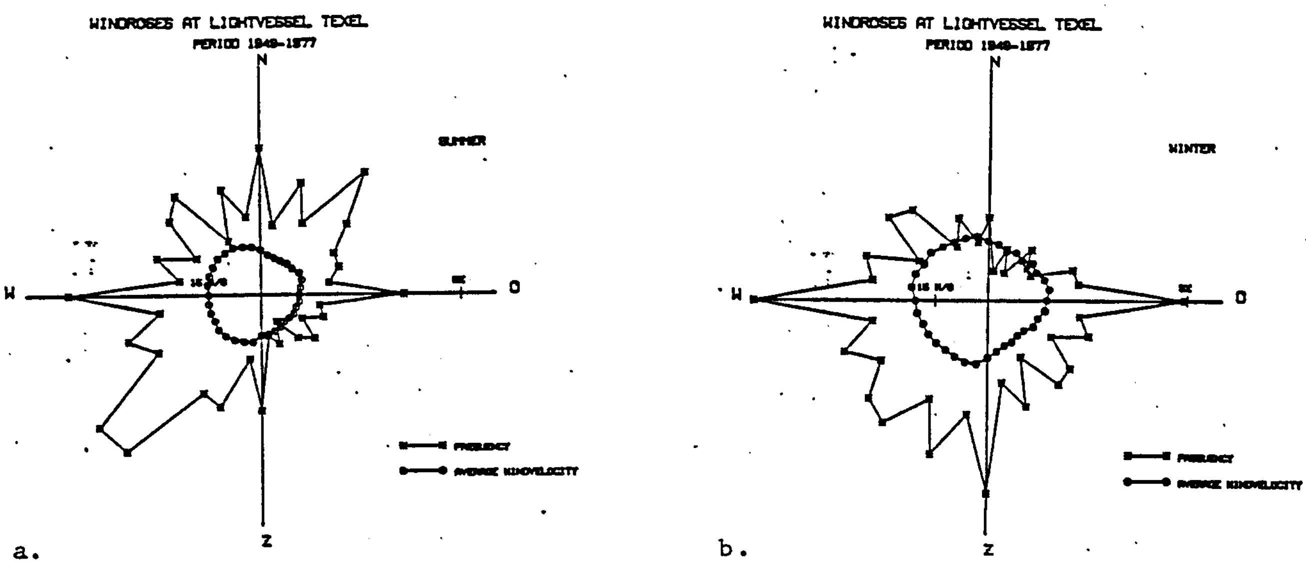


Fig. 1. Boundaries of the three nested models used for this study.



a. b.

Fig. 2. Statistics of wind, average velocity and frequency as a function of wind direction. (a. summer; b. winter)

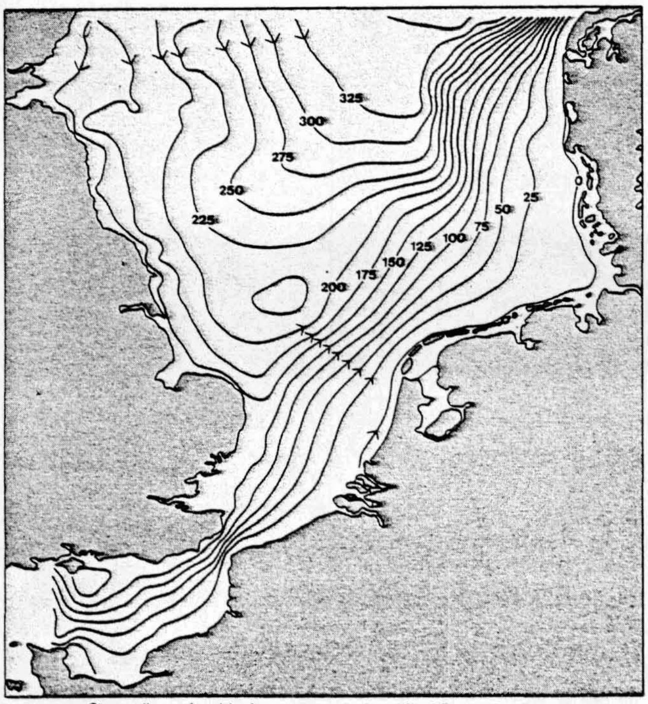


Fig.3a Stream lines of residual transport calculated for 4.5 m/s wind from the south-west (the direction of the long term mean of the wind stress) contour interval: 25000 m^3/s.

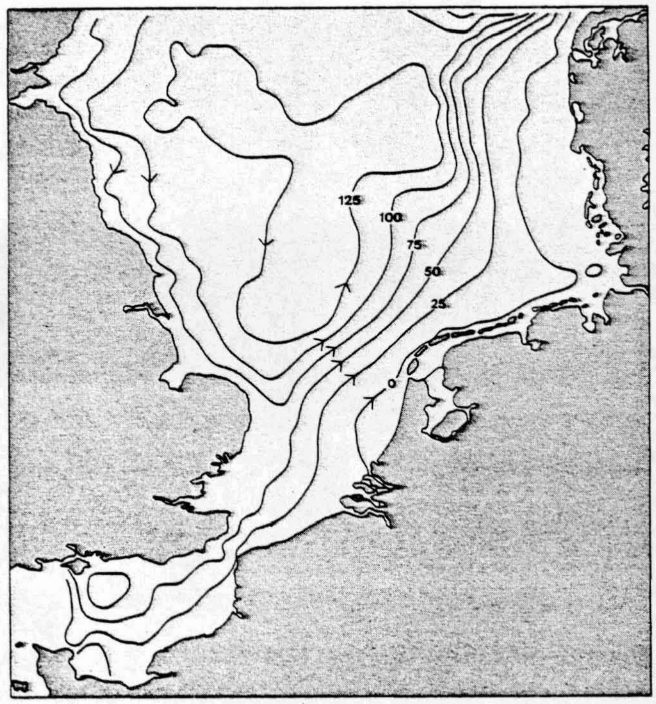


Fig.3b Stream lines of residual transport calculated for 3.5 m/s wind from the north-west.
(contour interval: 25000 m^3/s)

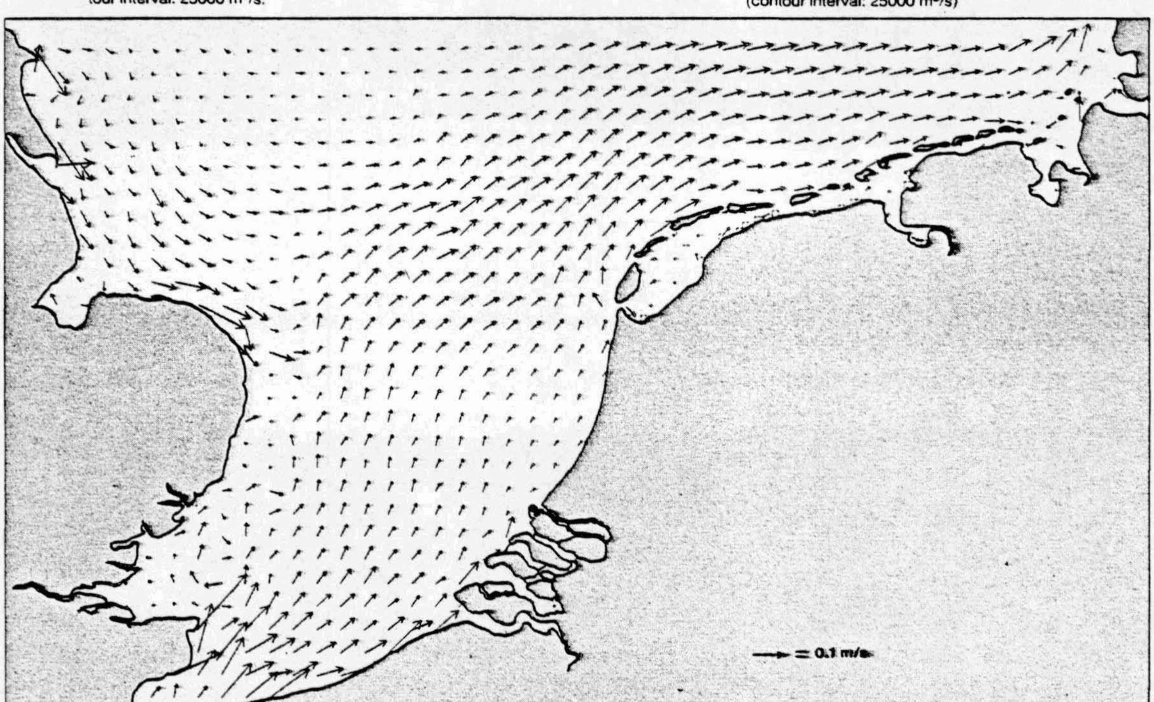


Fig. 4.

Calculated residual transport velocities for a 4.5 m/s southwesterly wind field.

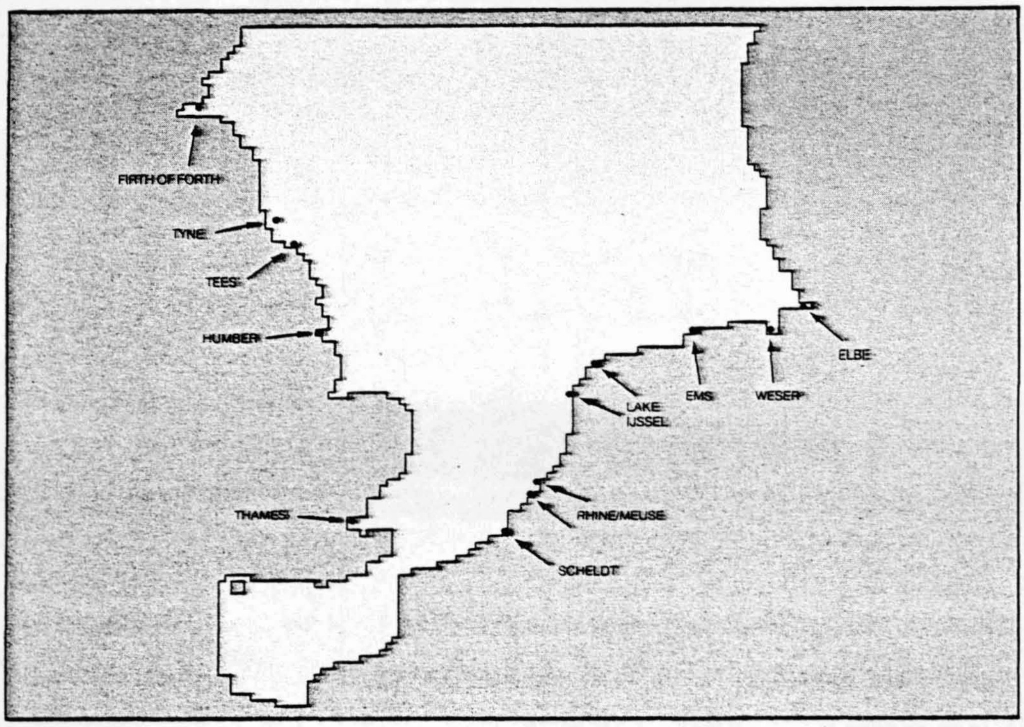


Fig. 5.

The area of the so-called 'overall model' of the southern North Sea. Arrows indicate positions of river inputs.

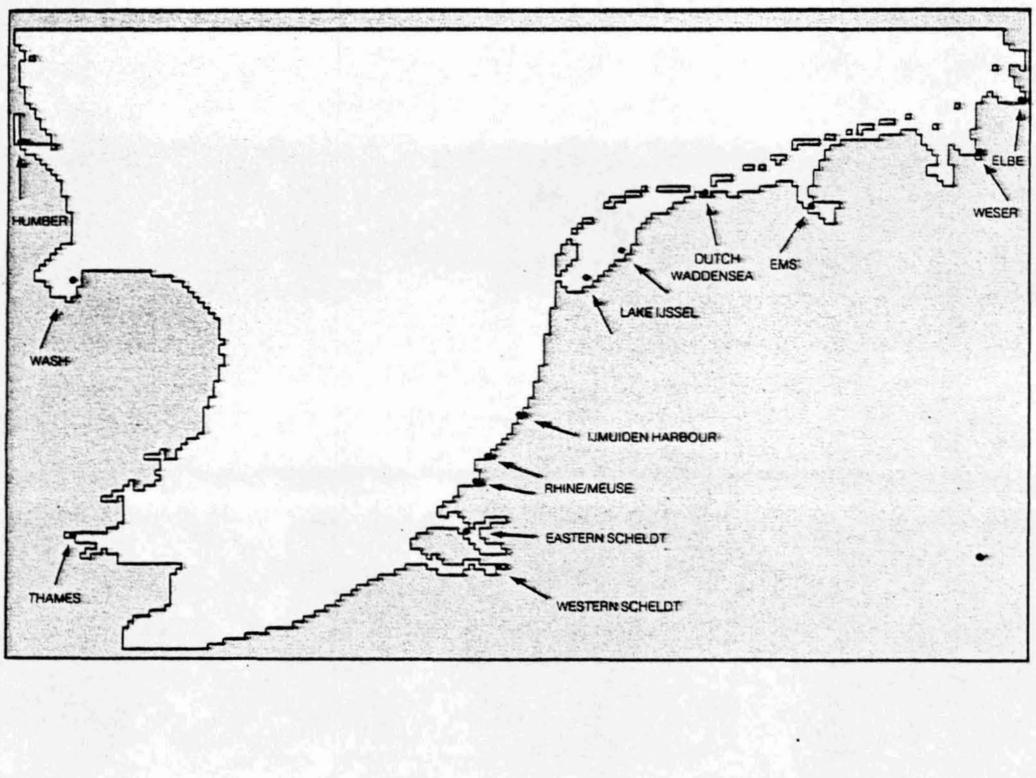
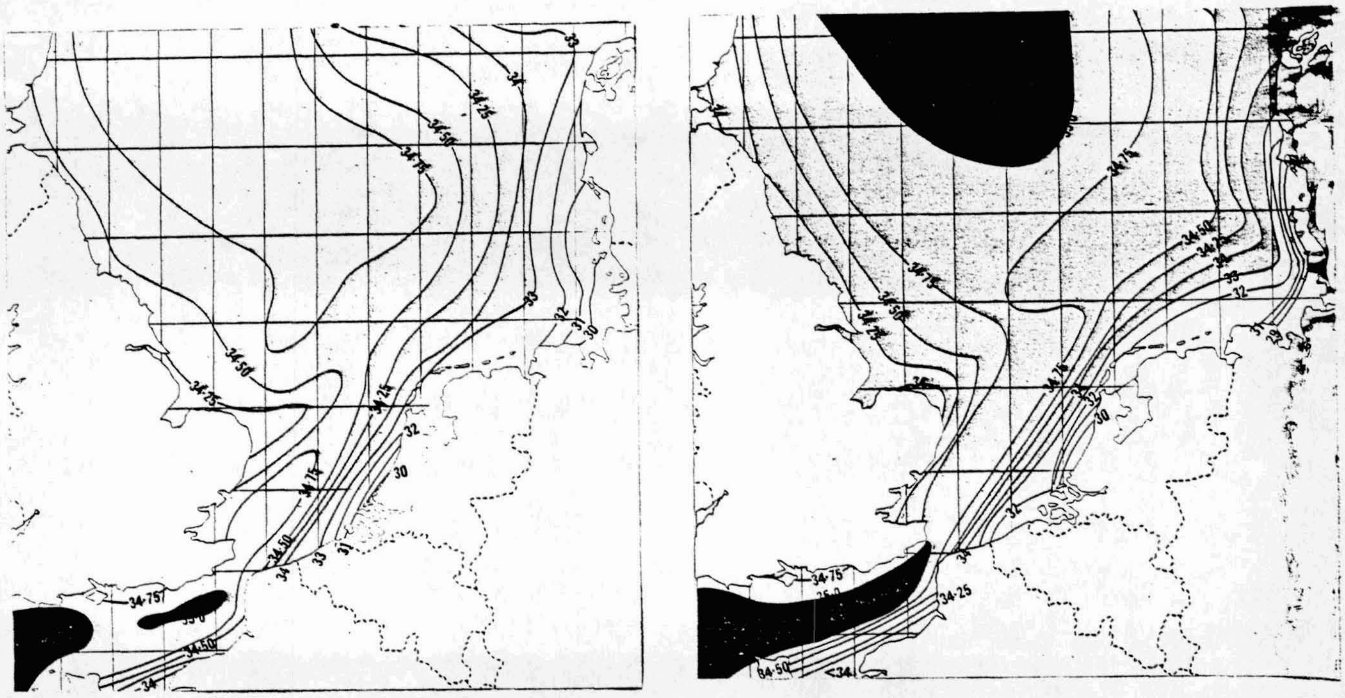


Fig. 6.

For detail model.



a. b.

Fig. 7. Measured salinity distribution (ICES, 1962).
(a. summer; b. winter)

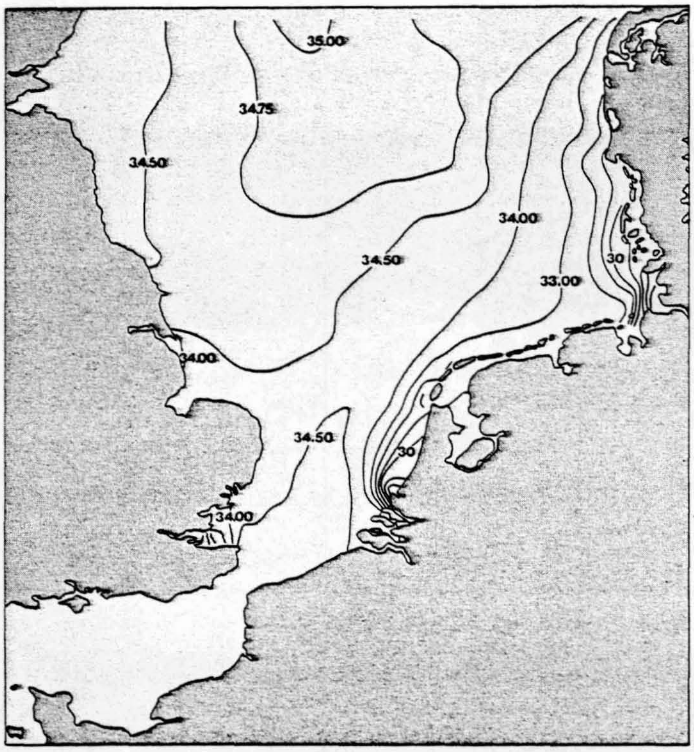


Fig. 8a.
Calculated salinity distribution (‰) in the overall model.

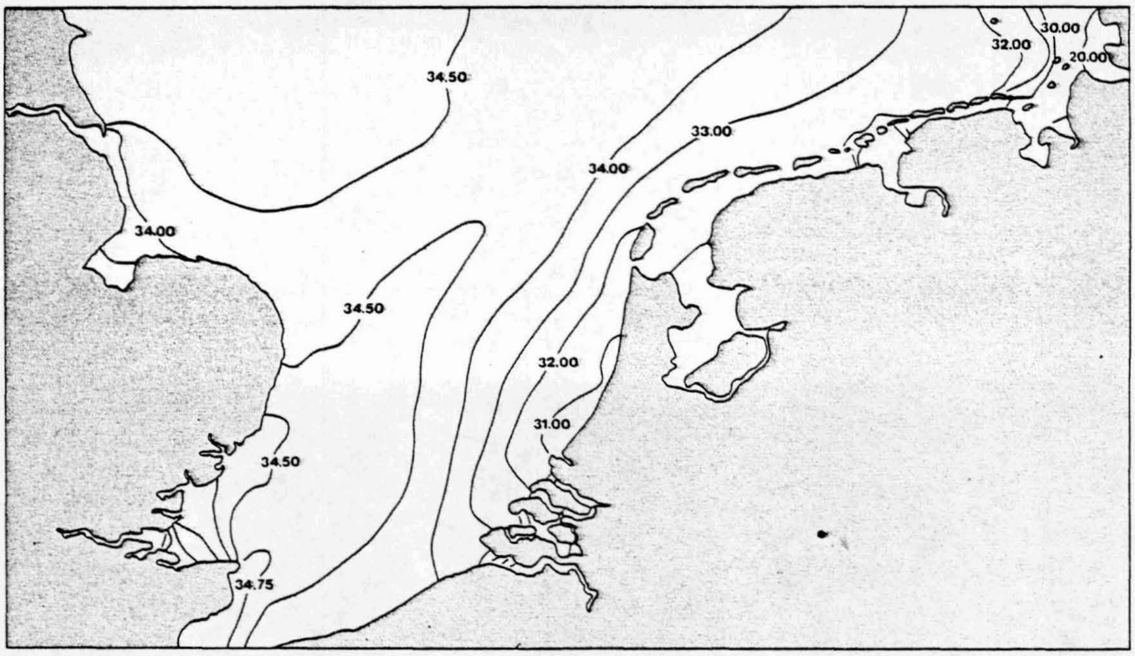
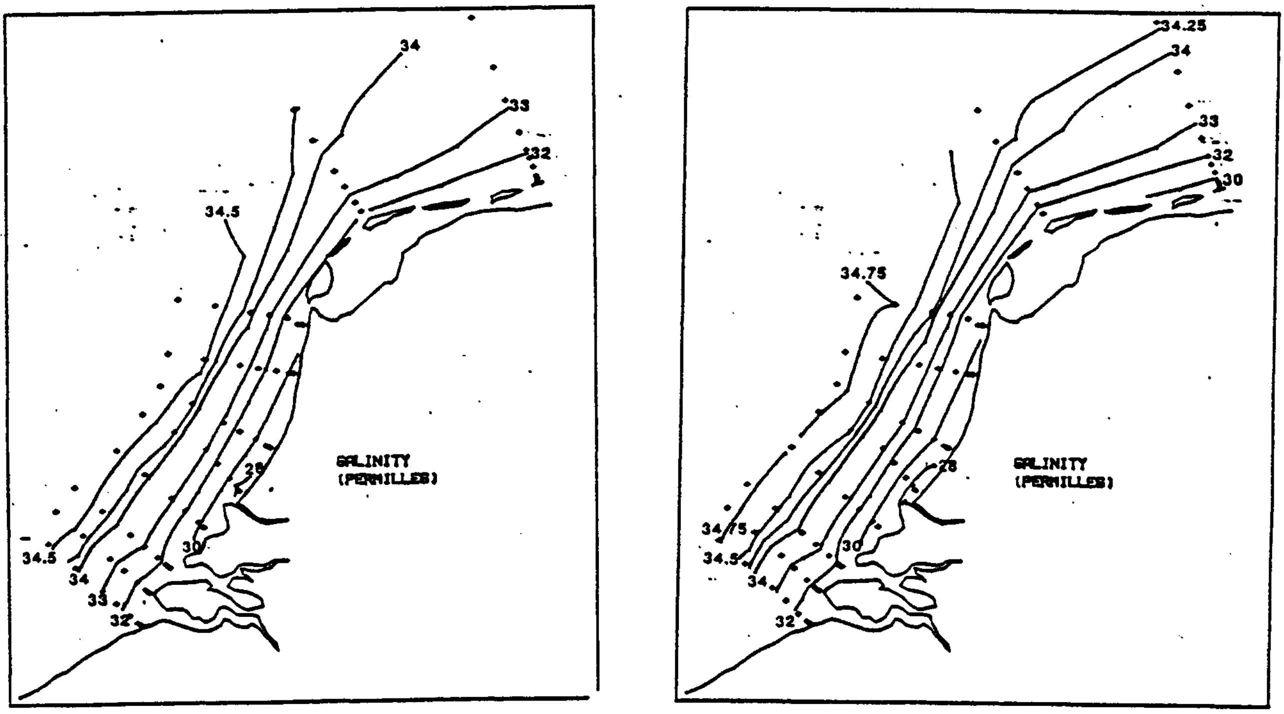
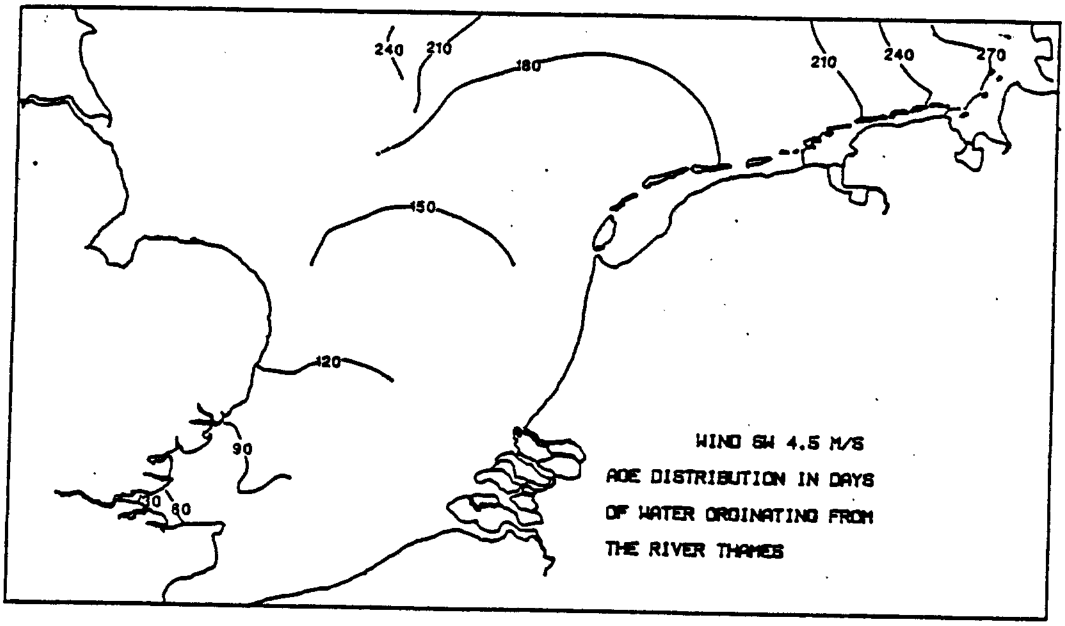


Fig. 8b. Calculated salinity distribution (‰) in the detail model.

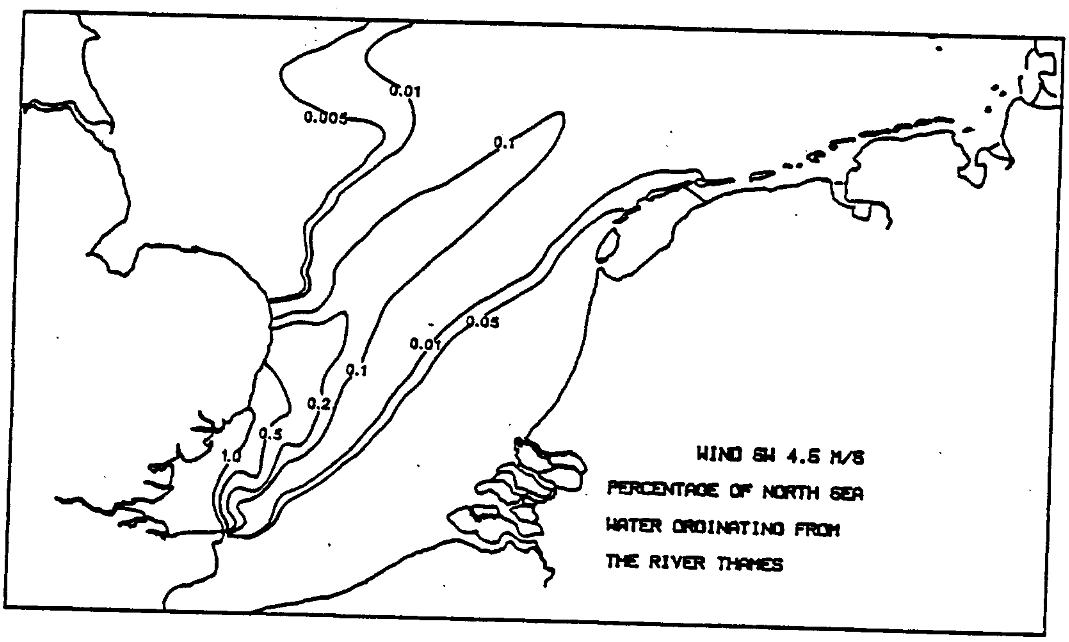


a. b.

Fig. 9. Salinity distrtibution along the Dutch coast. (a. summer; b. winter)

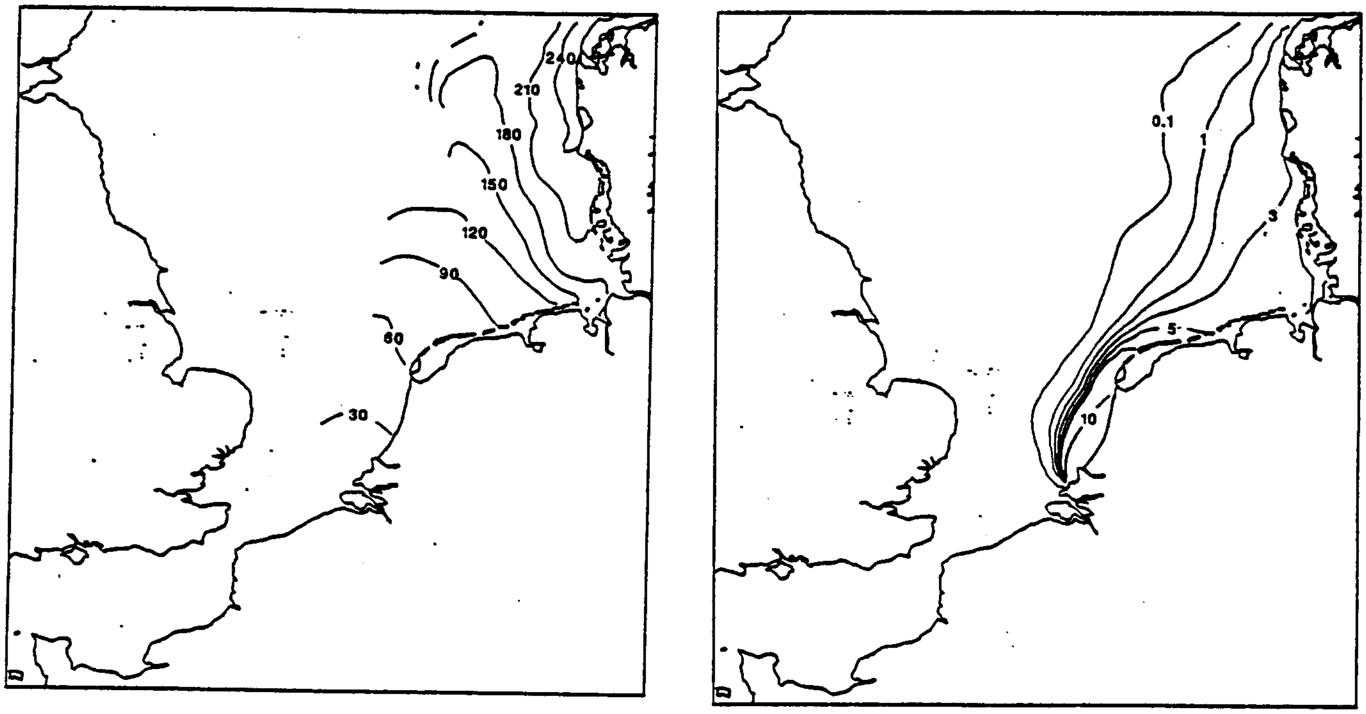


a.



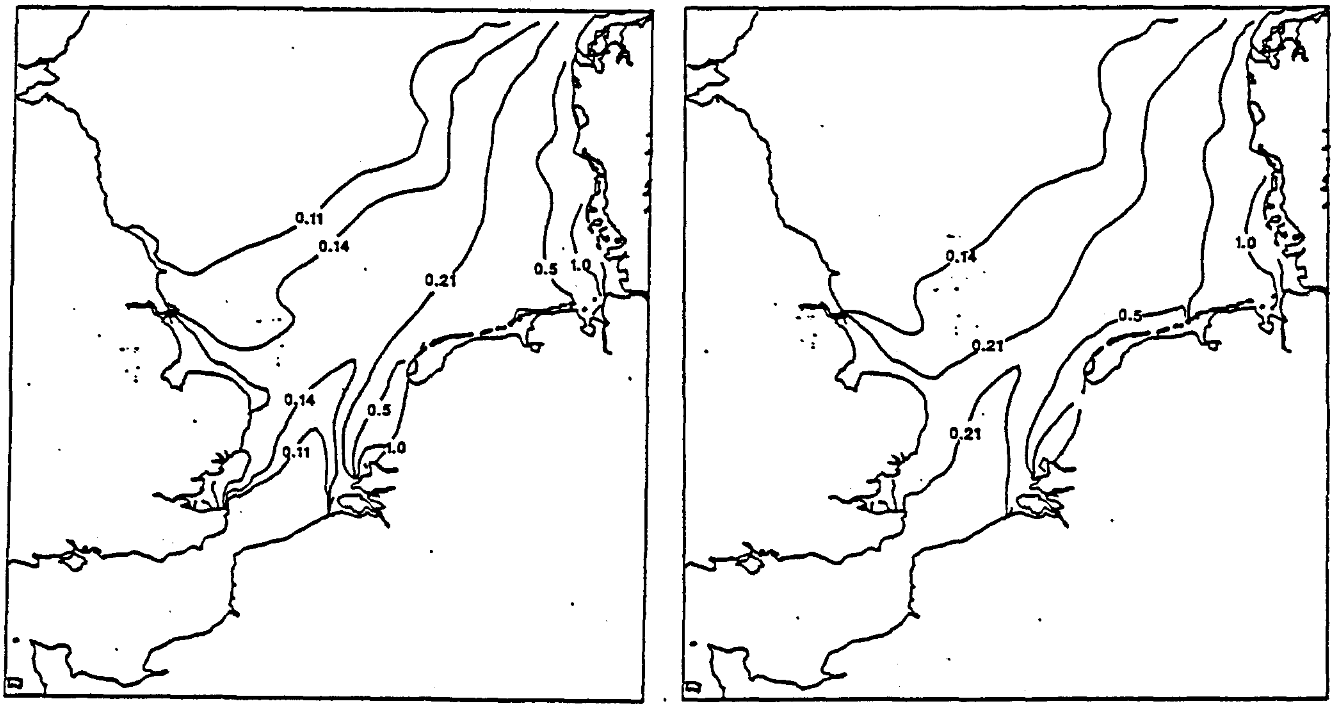
b.

Fig. 10. Fraction and age of river Thames water (a. age in days; b. amount of river water in percents)



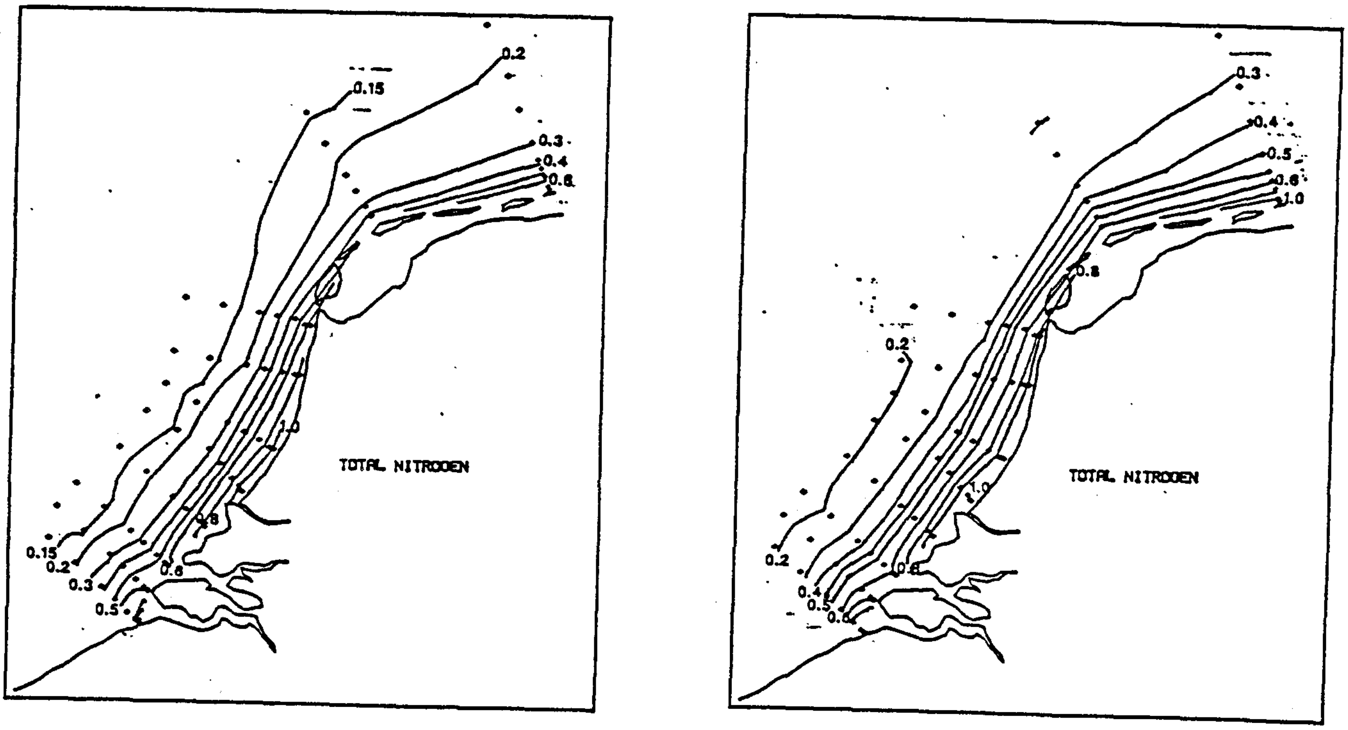
a. b.

Fig. 11. Fraction and age of river Rhine water. (a. age in days; b. amount of river water in percents)



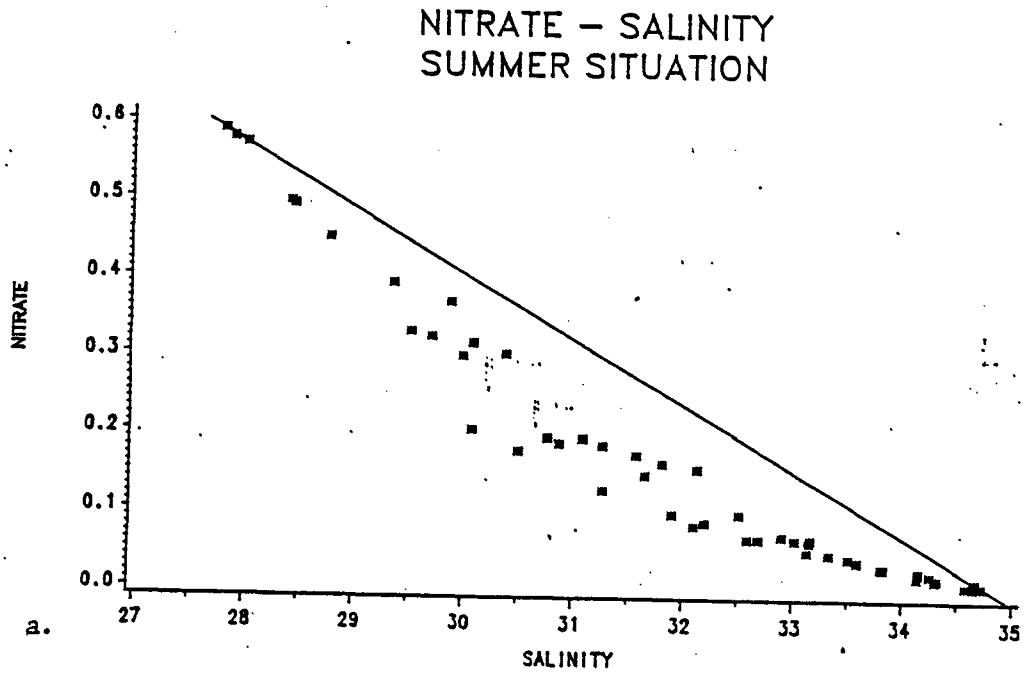
a. b.

Fig. 12 . Calculated concentration of total-Nitrogen (in mg/l).
(a. summer; b. winter)

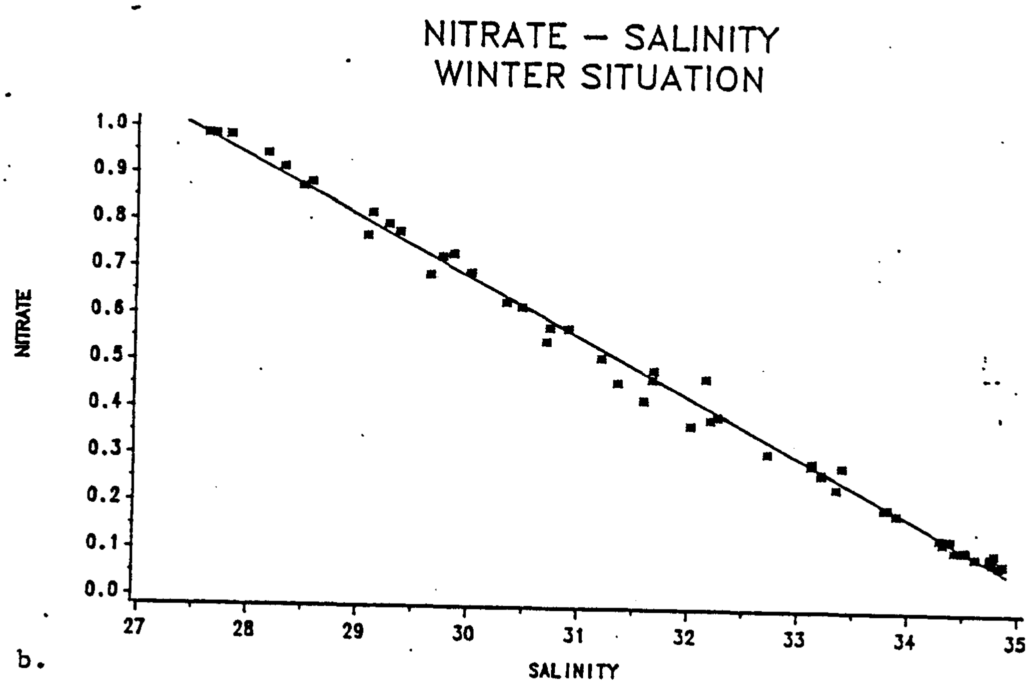


a. b.

Fig. 13. Measured concentration of total-Nitrogen along the Dutch coast.
(a. summer; b. winter)

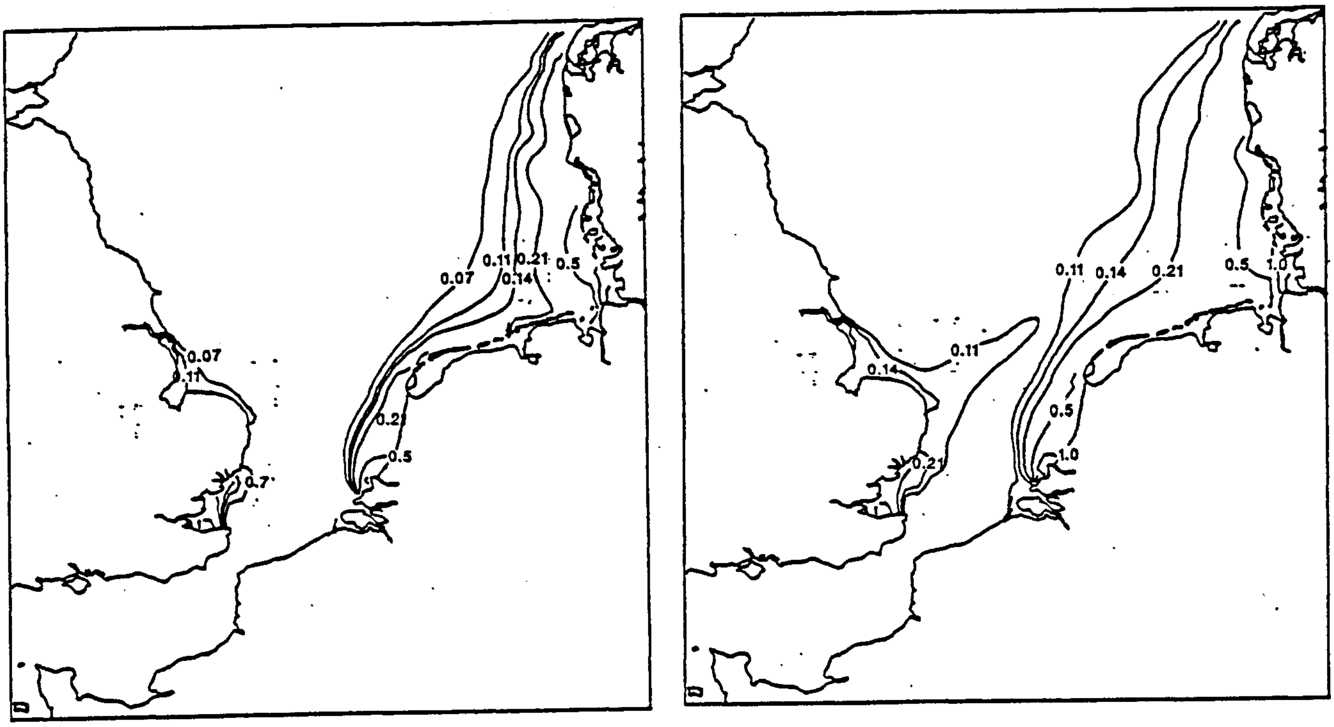


a.



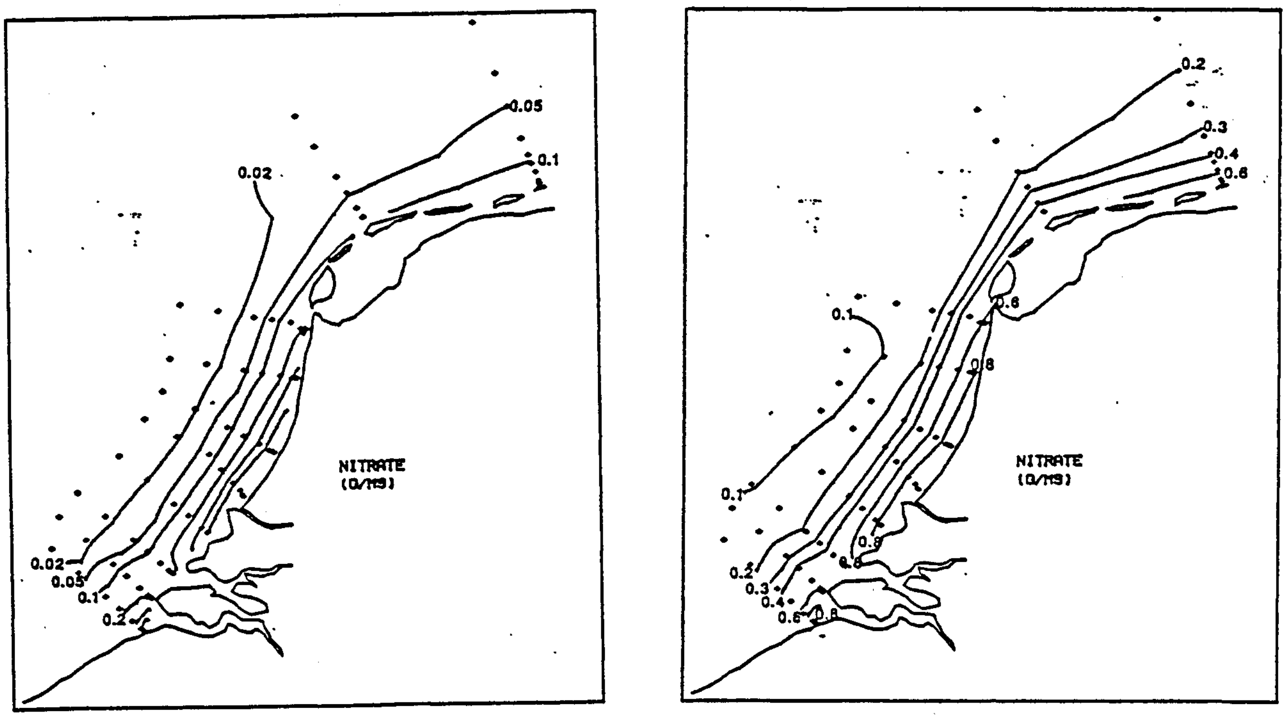
b.

Fig. 14. Correlation of nitrate cocnetration and salinity along the Dutch coast. (a. summer; b. winter)



a. b.

Fig. 15. Calculated concetration of nitrate (in mg/l).
(a. summer ;b. winter)



a. b.

Fig. 16. Measured concentration of nitrate along the Dutch coast. (a. summer; b. winter)

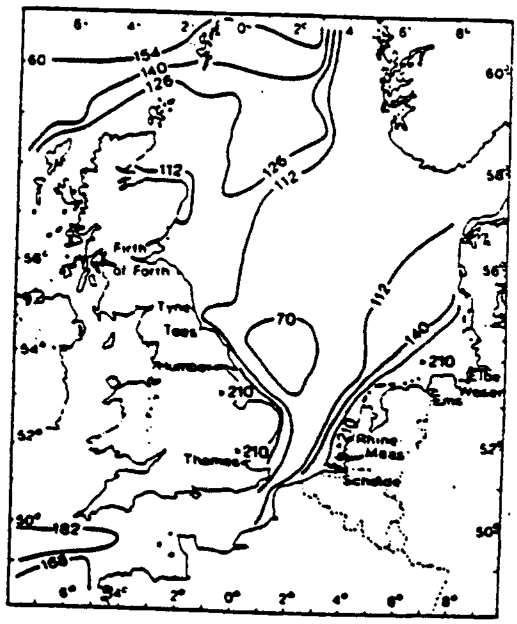
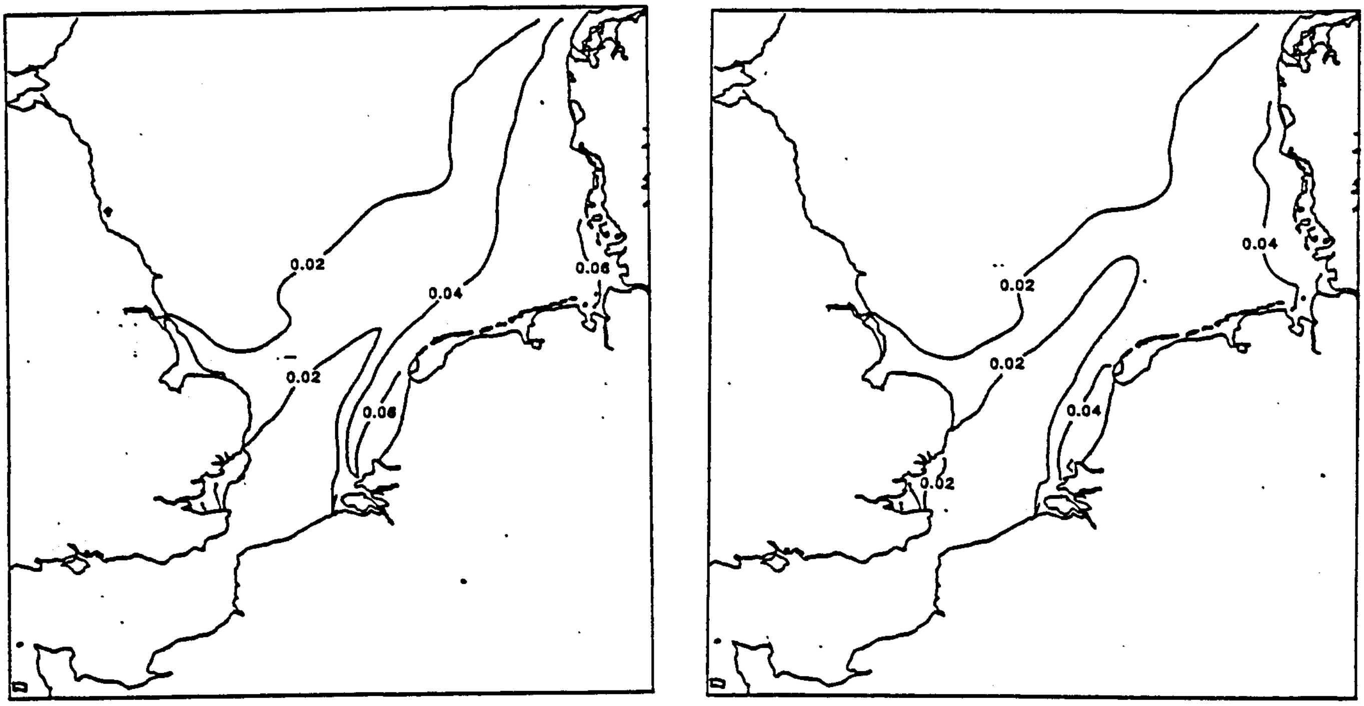


Fig. 17. Measured concentration of nitrate (in mg/l) in midwinter (Johnston, 1973)



a. b.

Fig. 18. Calculated concentration of total Cadmium.
(a. situation of 1980; b. situation of 1985)

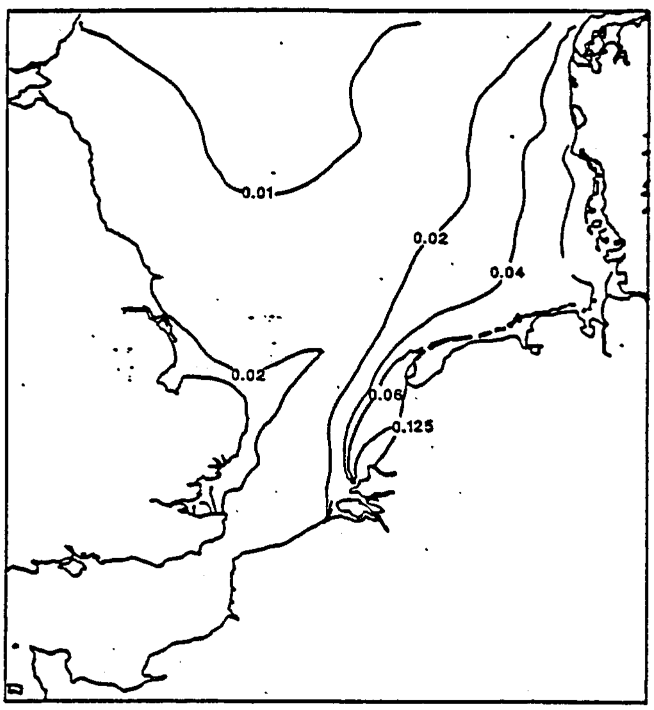


Fig. 19 simulated dissolved cadmium.

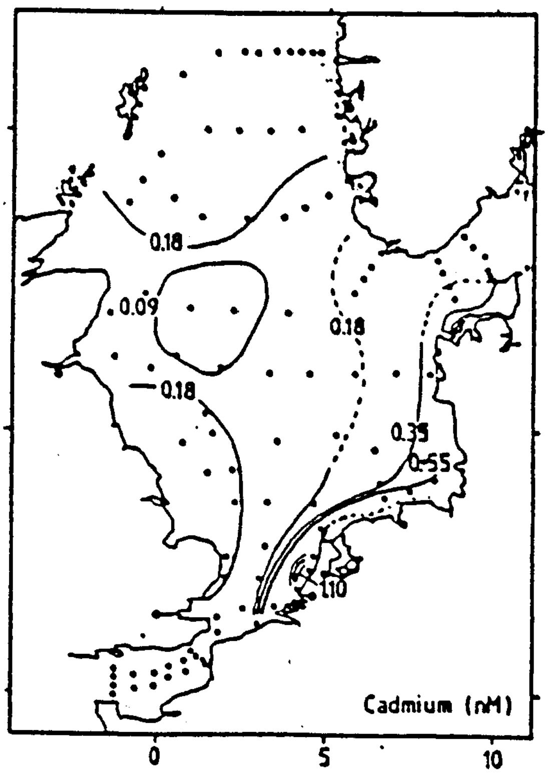


Fig. 20 dissolved cadmium at 10 m depth (jan-feb 1980) (Duinker, 1985).