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CALCULATION OF THE WATER EXCHANGE TIMES IN THE ICES-BOXES USING A HALF-LIFE TIME APPROACH

by

R. Luff and T. Pohlmann

Institut für Meereskunde
Universität Hamburg
Troplowitzstraße 7
D-22529 Hamburg; FRG

Abstract

The transport of passive dissolved and conservative matter is calculated with a three-dimensional Eulerian transport model in order to estimate the water exchange times for the ICES-Boxes. Daily flow fields calculated with a baroclinic circulation model (Pohlmann, 1991) are used to drive the transport model.

The half-life time of the concentration of a substance in a box is defined analogously to the half-life time of radioactive substances. To determine the half-life time for every ICES-Box, the water in this specific box is marked by a constant concentration, whereas the concentration outside the box is set to zero. The calculation stops when the concentration of matter in the box reaches 50 percent of its initial value.

In the classical approach the total exchange of water in a box is defined by the time that is needed for the total box mass to flow through the open boundaries of the respective box (flushing-time approach). Problems arise from this method if the flow field is very inhomogeneous or mesoscale eddy structures are located adjacent to the ICES-box boundaries (e.g. in the Skagerrak) because the flushing-time approach does not account the sign of the direction of the flow. It is based on the assumption of a homogeneous, straight flow through a box. On the other hand the half-life time approach takes into account the structure of the underlying flow field. Thus it is possible that matter leaves a box and returns, according to a change of the flow field. In such a situation the concentration in the box may increase, and induces a longer exchange time than by using the flushing-time approach.

Depending on the starting time there are significant inter-annual deviations between the half-life times for individual boxes. In comparison with the classical flushing-times approach used by Davies (1983), Backhaus (1984), Lenhart (1990) and Lenhart & Pohlmann (1995) the results of the method presented here show that in boxes with a predominantly inhomogeneous flow field (concerning the ICES-Boxes 3a, 4, 5a, (6b), 7a and 7b) the amount of time needed to reduce the concentration of a contaminant is probably longer than assumed up to now. This is caused by the fact that in these boxes the flushing does not only depend on the strength of the flow but also on the structure of the flow field, which is not taken into account in the flushing-time approach.

Introduction

The transport and dispersion of dissolved matter is important for the ecology of the North Sea. There are above all two types of passive, dissolved matters in the sea : nutrients and toxic agents. The nutrients Nitrogen (N) and Phosphorus (P) are naturally substances, but to a large extent they originate from human activities. Their predominant effect is to speed up the growth of phytoplankton and as a consequence they are responsible for the reduction of the oxygen concentration in the water (Radach et al. 1990). On the other hand many of the toxic substances are harmful to the ecosystem even in low concentrations. These substances enter the North Sea via rivers, directly from the share, the atmosphere, ships and the offshore industries. The knowledge of exchange-times, especially in the shallow waters adjacent to the main sources is an important piece of information which helps to detect particularly endangered areas of the sensitive ecosystem. Thus the results of these calculations might be useful be used for international commitments concerning the protection of the ecosystem North Sea.

To calculate the half-life times of the water exchange for the ICES-boxes, a three-dimensional dispersion model is applied. For each calculation of the half-life time of a box, the model was initialised with a constant concentration inside the box and with zero concentration outside. The concentration inside the box is used to mark the water at the moment of the initialisation. Advective and diffusive processes are responsible for the transport of matter out of the box and the resulting dilution and decrease of the concentration inside the box. Due to the nature of dilution it is impossible to achieve a final concentration of zero percent. Therefore a half-life time for the water exchange is defined analogously to the half-life time of radioactive substances. Using this definition the calculation stops when the concentration of matter in the box reaches 50 percent of its initial value. The difference between the half-life time approach and the classical flushing-time approach is, that the half-life time approach takes into account the structure of the underlying flow field. Thus it is possible that matter first leaves a box and returns later, according to a change of the flow field. In such a situation the concentration in the box may increase, and an exchange time that is longer than estimated by the classical flushing-time approach is the result.

To get an impression of the variability of the flow field and beyond that of the variability of the flushing-times, the calculations were carried out four times per year, beginning at the 1st of January, the 1st of April, the 1st of July and the 1st of October. The results of these calculations are the half-life times of water exchange for the ICES-Boxes 1 to 7b over a period from the 1st of January 1983 to the 1st of October 1993.

The model structure

The model structure includes three different hydrodynamic models shown in Fig 1. Two models (the 3-D baroclinic shelf sea model and the 3-D baroclinic North Sea model) are responsible for the calculation of the flow field. The third calculates the dispersion of matter in the sea using the flow fields calculated by the other models.

The flow field was taken from the results of a three-dimensional baroclinic primitive equation North Sea model, based upon a semi-implicit scheme (Pohlmann 1991). This model uses the sea surface elevations at the open boundaries prepared by a three-dimensional baroclinic shelf sea model (Backhaus 1985, Pohlmann et al. 1987, Pohlmann 1991). The shelf sea model encloses the North Sea, the adjacent shelf regions and parts of the deeper North Atlantic. The meridional spacing of the spherical model grid is 12 min, the zonal distance is 20 min, the vertical is resolved by 12 layers. The model is forced by climatological mean temperature and salinity distributions, the M_2-tide, and (three hourly) surface wind stress (according to Luthardt, 1987) and air pressure fields, all shown in the upper part of Fig. 1. The results of these calculations are the sea surface elevations at the open boundaries of the North Sea model at every time-step.

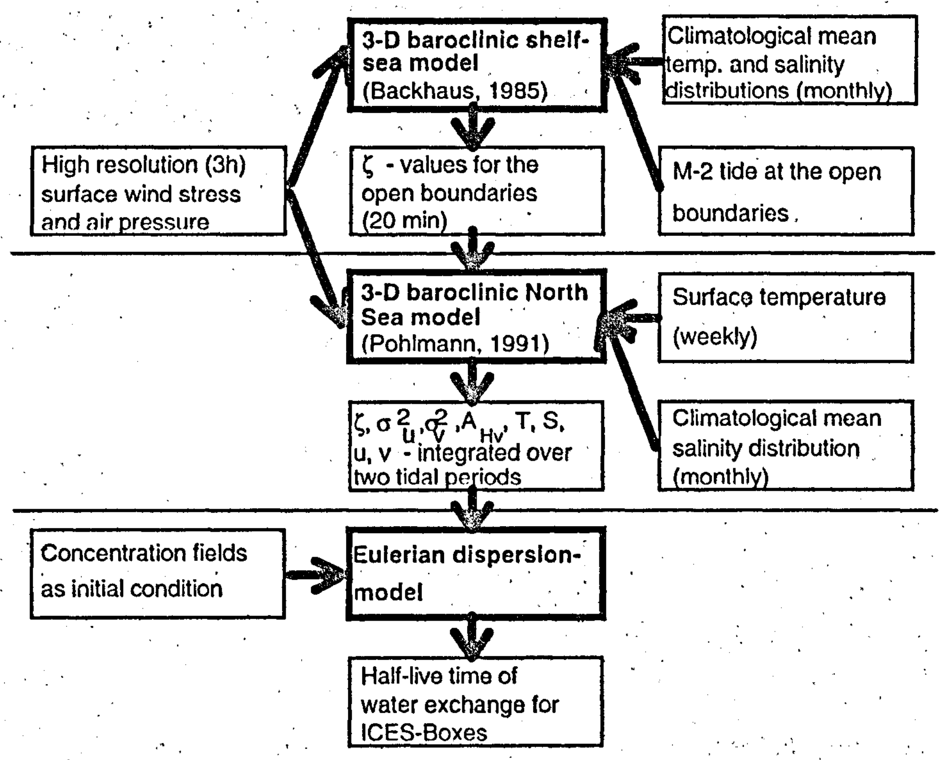

Fig. 1: Model configuration with the boundary values in the left and right boxes, and the models in the bold central boxes (Luff 1994).

To drive the North Sea model (Fig.: 1 middle part) weekly sea surface temperatures, the climatological salinity distributions and the surface wind stress and air pressure fields were used. This model has the same horizontal resolution as the shelf sea model, but it encloses only the region from 5°W to 14°E and from 49°N to 61°30'N. Fig. 2 shows the model domain of the North Sea model with the position of the model grid points and the position of the ICES-Boxes. In the vertical the model is resolved by 19 layers with a resolution of 5m per layer in the upper 50m in order to accurately describe the thermocline dynamics. Below 50 m the layer thickness increases with the depth. The simulations were carried out with a time step of 20 minutes.

The results of the North Sea model simulations are the flow fields, u and v, the variances of the flow fields, σ_u^2 and σ_v^2, the vertical exchange coefficients, A_{Hv}, the temperature and salinity distributions, T and S and the sea surface elevation ζ of the North Sea (Fig.: 1 middle part). All parameters are reduced by integration over two tidal periods. This long-term data set comprises these parameters over a period of 11 years, beginning at the 1st of January 1983.

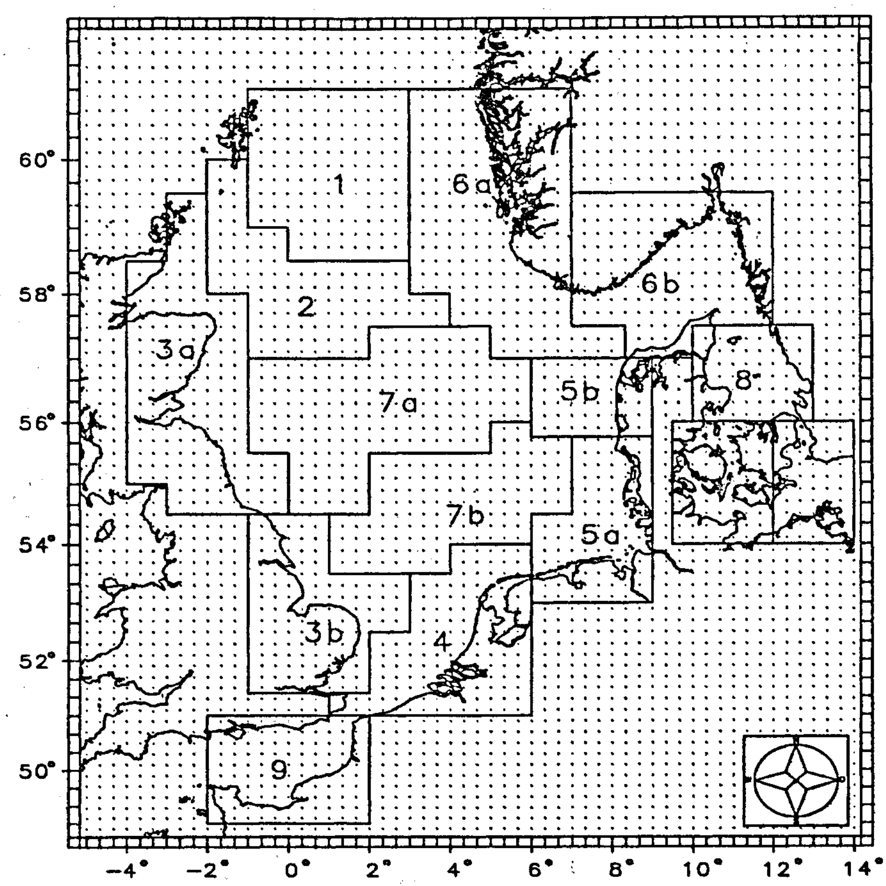

Fig. 2: The North Sea with the positions of the grid points used by the dispersion model and the ICES-Boxes.

The Dispersion model

In order to calculate the advection and diffusion of conservative dissolved matter a Eulerian dispersion model is used (Fig.: 1 lower part). In order to guarantee an optimum data exchange between the two models, the dispersion model uses the same grid resolution, encloses the same region and has the same time step as the North Sea model.

The equation for the calculation of the fate of concentration C of matter is analogous to the transport equation of temperature or salinity :

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(A_{HMx}\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_{HMy}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_{HV}\frac{\partial C}{\partial z}\right) + R_C$$

where R_C represents a source, in this case the initial concentration in the ICES-Boxes. To calculate the horizontal advection of the dissolved matter, the flow fields from the North Sea model (u and v) are used. The vertical component of the flow field to calculate the vertical advection is given by the equation of continuity from u, v and ζ.

To calculate the horizontal diffusion of matter it is necessary to determine the horizontal diffusion coefficients A_{MHx} and A_{MHy} using the variances σ_u^2 and σ_v^2 of the flow field. Here, a scheme suggested by Maier-Reimer (1973) is used :

$$A_{MHx} = \frac{1}{2} * \sigma_u^2 * \frac{T}{2}$$

$$A_{MHy} = \frac{1}{2} * \sigma_v^2 * \frac{T}{2}$$

Where T denotes one period of the M_2-tide (suggested by van Dam, 1994).

A Eulerian dispersion model is usually used for long-term calculations. The advantage of this model type over a Lagrangian formulation is that there is no limit in time or space due to the minimum amount of particles needed for meaningful results : the statistical interpretation of the results, using a limited number of particles to estimate a concentration in a box is uncertain. The disadvantage of the Eulerian dispersion model is the presence of numerical diffusion and in some cases the non-preservation of the dissolved mass especially when strong concentration gradients are present.

The comparison between a simulation with a Lagrangian dispersion model from Müller-Navarra & Mittelstaedt (1987) and the present Eulerian model, for realistic horizontal gradients however reveals that the numerical diffusion of the Eulerian model does not cause any severe limitations (Luff 1994).

In the present study a "*mass component upstream*" algorithm was chosen for the advection. A simulation to test the conservation of mass shows, that after 150 days of simulation the difference between the initial mass and the mass remaining in the model system amounts to only three percent (Luff, 1994).

Flushing-time - half-life time

In the classical calculation method, the flushing-time approach used by Davies (1983), Backhaus (1984), Lenhart (1990) and Lenhart & Pohlmann (1995), the total exchange time is defined by the time that is needed for the total box volume to flow through the open boundaries of the respective box. The equation used by Davies, Backhaus, and Lenhart for the turnover time T is usually expressed as the ratio of the total amount of water in the box to the total flux, according Bolin & Rohde (1973).

$$T = \left(\frac{V}{S}\right)$$ with : V = total volume in the reservoir [m^3]

S = total flux through the open boundaries of the box [m^3 / s]

This assumption is correct as long as the flow field is sufficiently homogeneous, and the direction of the flow does not change its sign e.g. in a river without tide. However due to the shallowness of the North Sea the influence of the weather may cause a significant temporal variability of the flow field. Additionally, mesoscale eddy structures are present in some regions of the North Sea (for example in the Skagerrak and near the British Channel) causing a strong spatial variability. Both kinds of variability may lead to significant errors in the water exchange time of a box calculated under the assumptions of the flushing-time approach. This is the main reason why flushing-times presented by different authors vary significantly depending on the temporal resolution of the forcing data. A detailed discussion of this problem is given by Lenhart & Pohlmann (1995).

By employing the dispersion of passive conservative matter in order to calculate water exchange times these problems will be avoided. This is possible because temporal and spatial resolution of the dispersion model also allows to resolve processes which have considerably smaller scales than the ICES-Boxes. It is possible for matter to leave a box and return again according to the flow field and thus for the concentration in a specific box to rise. In such a case the flushing-time will become decisively longer than with the classical approach that does not take into account the direction of the flux. That is the main reason why this study uses the half-life time approach instead of the flushing-time approach to calculate the water exchange in the ICES-Boxes.

Results of the calculation and discussion

The results of the calculation using the half-life time approach are shown in table 1 for the ICES-Boxes 1 to 7b. For the 11 years 44 calculations of the half-life times were carried out in order to calculate the minimum, maximum, mean- and median values and the standard deviation for each box.

As expected the longest periods for a mean half-life time are in the boxes 7a and 7b, in the central North Sea where the corresponding currents are very weak. It is interesting to note, that these boxes exhibit large differences between the maximum and the minimum value, with 87 days for box 7a and 81 days for box 7b.

	Volume	**Half-life times of water exchange in the ICES-Boxes in days**				
BOX	[km³]	Min	Max	**Mean**	Median	Std Derv
1	6.352	15	59	**42**	43	9.7
2	4.522	11	42	**27**	27	7.2
3a	2.174	17	68	**43**	45	10.6
3b	635	7	19	**15**	15	2.9
4	1.263	9	71	**43**	41	18.4
5a	644	10	78	**44**	42	20.9
5b	528	3	29	**12**	11	7.2
6a	13.177	13	46	**34**	34	8.1
6b	6.572	28	122	**64**	54	26.4
7a	5.520	22	109	**75**	76	23.9
7b	2.443	11	92	**53**	57	22.7

Tab. 1: Results of the calculation with the dispersion model for the half-life times of water exchange in the ICES-Boxes 1 to 7b for the years 1983 to 1993.

High transport rates (up to $2.0 * 10^6$ m³/s) are responsible for the relatively short mean half-life time of 34 days in box 6a (west of Norway), the box with the largest volume. This box shows relatively constant half-life times over the years, with the shortest times in winter and the longest in spring.

The results of the half-life time calculations for the ICES-Box 6b reflect the influence of the large cyclonic eddy structure and the outflow of the Baltic Sea water. Luff (1994) calculated the transport through the Skagerrak perpendicular 8°40' E. Strong currents of up to 1.3 * 10^6 m^3/s dominate this section with westward flow in the north and eastward flow in the south in the upper 100m. In spite of these strong currents the mean half-life time of 64 days is the second highest one and the standard deviation has its maximum value in this box. Because of the enormous variance of the currents near the surface and the large depth of the box the half-life times often reach values above 100 days and with its maximum of 122 days the longest half-life time from all the calculations.

The overall shortest exchange time can be found in box 5b (west of Jutland), where the Jutland Current with transport rates of up to 0.6 * 10^6 m^3/s (Luff 1994) in combination with the small volume of this box is responsible for very short half-life times. The minimum of three days is an indication that one single storm event is able to reduce the concentration to half its initial value in this box.

In Fig. 3 all the calculated half-life times of water exchange for the ICES-Box 5b are shown. Each bar represents one calculation, demonstrating the strong inter-annual fluctuations in the exchange times.

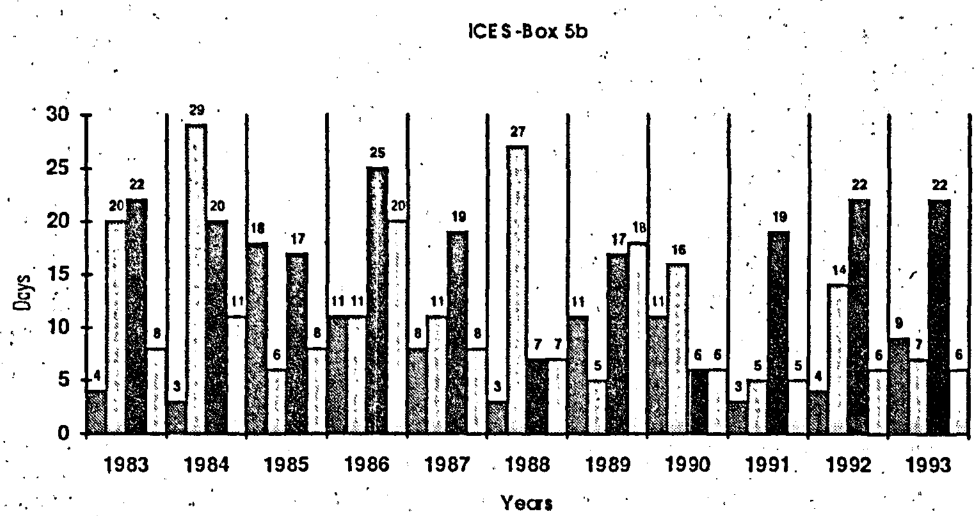

Fig. 3: Half-life times of water exchange in ICES-Box 5b in days for the 11 years of simulation depending on the starting date of the calculation.

The ICES-box 5b is mainly influenced by dissolved matter from the sources Rhine, Weser and Elbe on the one hand and on the other hand from the Jutland current and connected strong turbulence. The half-life time of water exchange in this box depends mainly on the strength of the Jutland current. In general the direction of the Jutland current is directed northward, but in spring it is often reversed (Luff, 1994). In winter the Jutland current has its largest transport rates of up to 0.6 * 10^6 m^3/s, which are responsible for the very short half-life times in this box. In spring 1984 and 1988 the transport of the Jutland current had very low values (0.05-0.1* 10^6 m^3/s) additionally showing a southward component. Thus the half-life times reach their maximum of 29 and 27 days in these years.

Fig. 4 shows the calculated half-life times for the ICES-Box 7a (central North Sea). The calculations in this box exhibit a strong inter-annual signal in the water exchange. In winter the half-life times are in general the shortest ones with a mean value of 53 days. In spring they reach their maximum with a mean value of 100 days; in summer the mean value is 87 and in autumn it is 60 days.

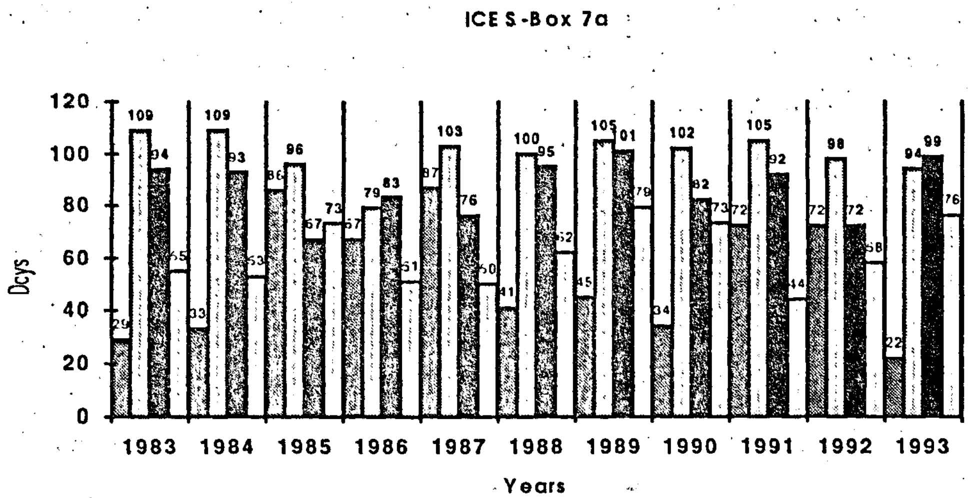

Fig. 4: Half-life times of water exchange in ICES-Box 7a in days for the 11 years of simulation depending on the starting date of the calculation.

As an example Fig. 5a and b demonstrate the development of the concentration of box 4, and box 6b for the first 11 starts. In general the strong gradients at the open boundaries of the boxes decrease during the first few days. This can be concluded from the fact that the decrease of concentration in the box is most pronounced during the first days of the calculations. About 15% of the mass leave the box during the first few days. As mentioned above in such an extreme situation the numerical diffusion may contribute significantly to the total dispersion. After this period the gradients are smoother and the decrease of matter in the box per day becomes smaller.

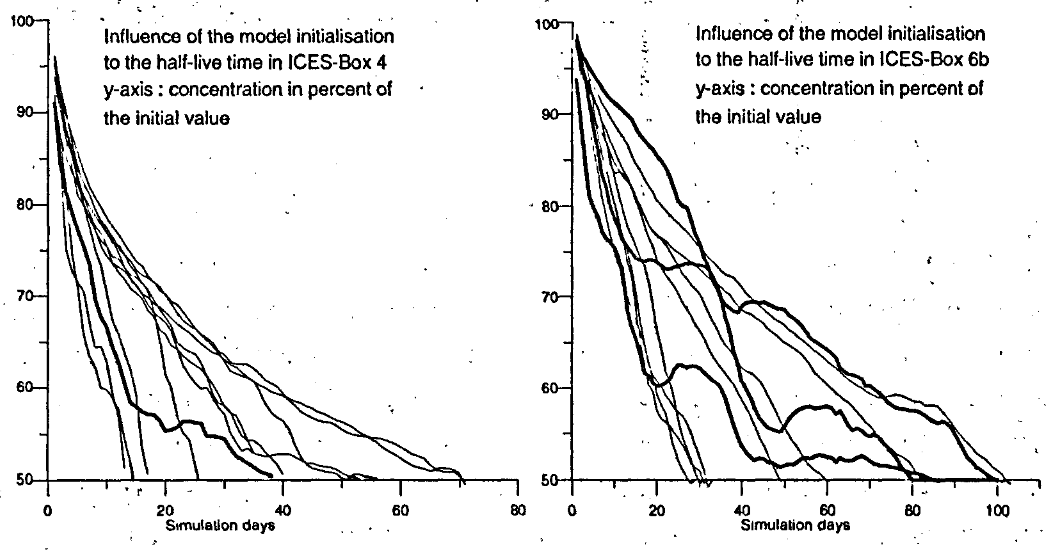

Fig. 5a and b: Time series of the concentrations in percent of its initial value from 1st of Jan. 1983 to 1st of July 1985 depending on the start time of the simulation. Left : ICES-Box 4 (in front of the Belgium and the Netherlands coasts), right : ICES-Box 6b (Skagerrak)

Tests in which the time from half to quarter concentration were calculated (Luff, 1994) show that on average the first half-life time was about 10% shorter than the second one. Therefore it can be inferred that due to the presence of the strong gradients the half-life times presented in this study are likely to be underestimated by 10% to 15% as a result of numerical diffusion.

The curves in Fig. 5a represent the dilution of the concentration of box 4 (in front of the Belgium and the Netherlands coasts) starting at the 1st of January 1983 and the curves in Fig. 5b represent the dilution of the concentration of box 6b (Skagerrak). These figures clearly demonstrate the main difference between the flushing-times and the half-life time approach. By using the dilution it is possible that the concentration in a box increases again as can be seen from the bold curves. This for instance happens in ICES-Box 4 at the 20th of April 1985 when water with a higher concentration near the boundary of the box flows back into the box because of a change of the flow direction. In this case the concentration increases from 55.33 % of the initial value at the 20th of April 1985 up to 56.35% at the 24th of April 1985. Even more significantly this can be seen in Fig. 5b where the concentration in box 6b increases from 60.21% to 62.53% during five days.

Comparison of half-life times with flushing-times from other references

To put the calculated half-life times into a relation to earlier results on the subject of water exchange a comparison between half-life time and turn-over time is carried out. In table 2 the comparison between the half-life times calculated in this study and the flushing-times calculated by Davies (1983), Backhaus (1984), Lenhart (1990) and Lenhart & Pohlmann (1995) is shown. The main differences between the flushing-times given by Davies, Backhaus, Lenhart and Lenhart & Pohlmann may result from the different meteorological data and the different models they used. Davies (1983) used a wind stress distribution integrated over a period of three months to drive his vertically integrated model, while Backhaus (1984) used a high resolution atmospheric forcing data set for one summer period and a model with a vertical grid resolution of 12 layers in summer and 7 layers in winter. Lenhart (1990) calculated his flushing-times with a model based on the same model as the one used by Backhaus (1985) but with a vertical grid resolution of 12 layers in summer and winter, respectively. This model was forced by high resolution (6 hours, 150 x 150 km) air pressure and wind stress fields for the years 1977 to 1981. The underlying flow field used by Lenhart & Pohlmann (1995) is the same data set that is used for the calculation with the Eulerian dispersion model in this study.

The comparison between the half-life times and the flushing-times from Davies (1983), Backhaus (1984), Lenhart (1990) and Lenhart & Pohlmann (1995) in table 2 is given only for identical boxes. Davies did not use the separation of the boxes 3 and 5 in his flushing-times calculations, while Backhaus did not use the separation of box 5. None of the other authors calculate the flushing-times for the box 6b (Skagerrak). Thus there is no entry in table 2 for these boxes. Unfortunately, Davies and Backhaus do not specify the mean values of their calculation, so the main comparison is made between the results from Lenhart and Lenhart & Pohlmann and the half-life times calculated for this study.

The comparison between the turn-over times from Davies (1983), Backhaus (1984), Lenhart (1990) and Lenhart & Pohlmann (1995) and the half-life times calculated in this study is given in table 2. In most of the cases the half-life times are in the same order of magnitude as the flushing-times from Backhaus, Lenhart. and Lenhart & Pohlmann The significant differences between the flushing-times calculated by Davies and the half-life times may result from his meteorological forcing.

	Davies		Backhaus		Lenhart			Lenhart&Pohlmann			Half-life times		
BOX	Min	Max	Min	Max	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
1	180	1200	35	48	27	54	41	21	50	38	15	59	42
2	80	480	9	39	18	37	28	14	49	28	11	42	27
3a			13	41	19	50	33	18	73	36	17	68	43
3b			15	30	11	37	21	10	50	30	7	19	15
4	40	190	21	29	8	40	19	7	49	28	9	71	43
5a					9	49	26	10	56	33	10	78	44
5b					3	25	10	2	29	11	3	29	12
6a	140	650	41	61	33	60	47	20	57	38	13	46	34
6b											28	122	75
7a	110	350	32	49	25	54	38	19	68	40	22	109	75
7b	60	180	31	39	16	48	30	13	57	34	11	92	53

Tab. 2: Comparison of the flushing-times from Davies (1983), Backhaus (1984), Lenhart (1990) and Lenhart & Pohlmann (1995) with the half-life times (minimum, maximum and mean value) in days calculated with the dispersion model.

To compare the results, for the boxes with a predominantly homogeneous circulation (1, 2, 3b, 5b and 6a) the definition of a turn-over time from Prandle (1984) can be used as an approximation. This definition is analogous to the definition given by Bolin & Rohde (1973) (see above) for dissolved matter mixed in a homogeneous flow. Prandle defines the turn-over time for calculations with his dispersion model as the time for the total mass of material originally within a bounded region to be reduced to a factor e^{-1} (i.e. 0.37). His definition is based on the idea that the concentration in a box will be reduced by a homogeneous current and continuous mixing. After the turn-over time the total amount of water of the box was flown through its boundaries and the concentration in the box is reduced to 37% of the initial value. Consequently the comparison between the results from Lenhart, Lenhart & Pohlmann and the half-life times in table 2 for the boxes 1, 2, 3b, 5b demonstrates good agreement of the mean values as well as the maximum and minimum.

To get an impression of the meaning 'of the turn-over time' defined by Prandle (1984) (37 percent of the initial matter remain in the box) the distribution in percent of the initial values at the surface after one turn-over time is shown in Fig. 6a as an example for box 5b (west of Jutland). Even in this box that is dominated by a strong homogeneous current there are large areas where the concentration reaches values of above 50 percent.

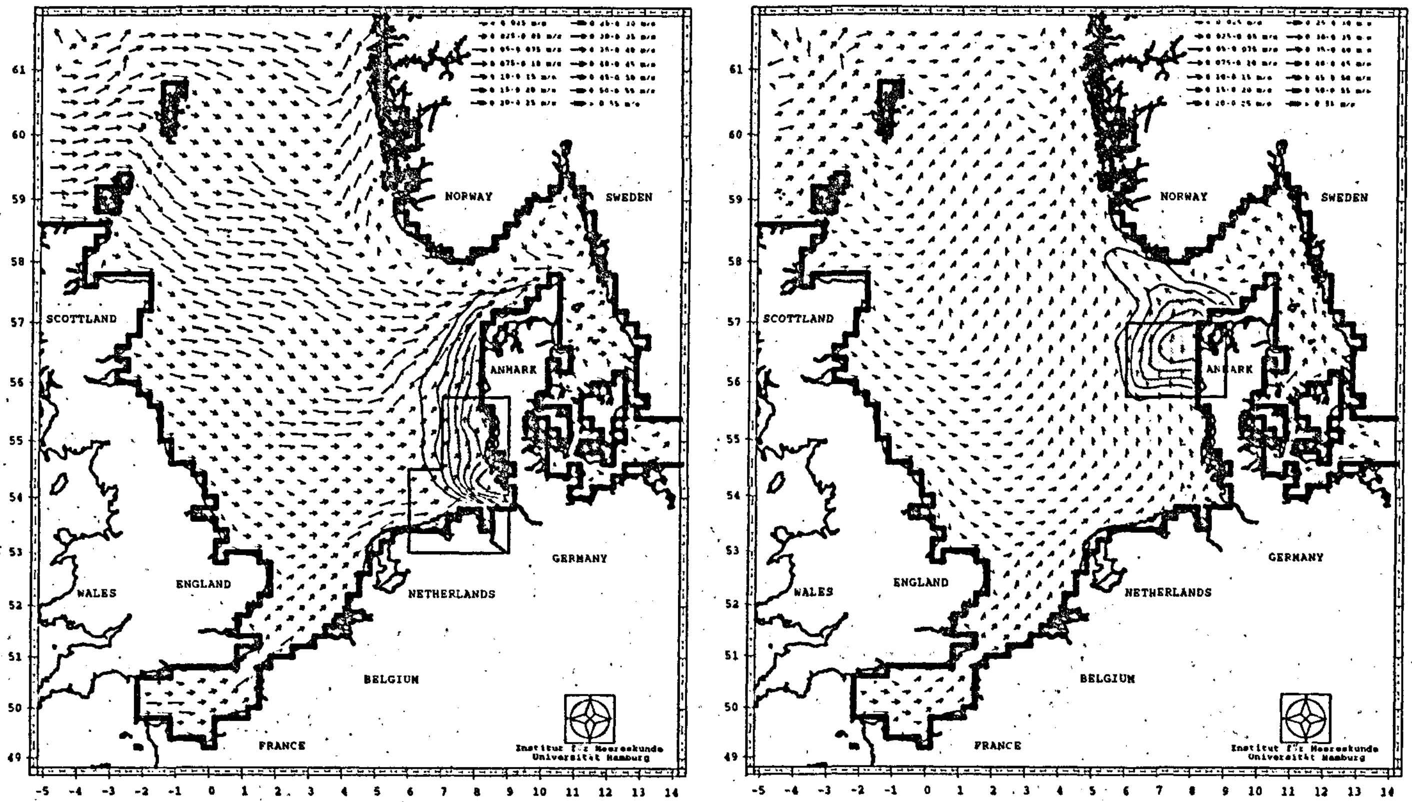

Fig. 6a and b: Distribution of the concentration in percent of the initial values at the surface after one turn-over time defined by Prandle (1984) together with the corresponding currents in m/s for ICES-Box 5a and ICES-Box 5b. In addition the relevant box boundaries are outlined. The contour line interval is 10 percent beginning with 10 percent.

In box 5a (German Bight) the concentration after one turn-over time shown in Fig. 6b even exhibits values up to 70 percent particularly in near-coastal regions. Because of this high peak of the concentration in the box, the water can not be regarded as exchanged. By calculating the water exchange time for a box in this way, it is easy to get a wrong impression of the water quality for example after a ship disaster, because the water in the box is defined as fully exchanged, even though in certain areas it still contains an immense concentration of contaminant. This clearly demonstrates the advantage of the half-life time approach over the flushing-time or the turn-over time approach. Using the half-life time approach a more realistic impression of the water quality after a certain amount of time can be expected.

Especially in boxes where the circulation is inhomogeneous (3a), where the main circulation influences only a part of the box (5a) or where mesoscale eddy structures are located adjacent to the box boundaries (4, (6b), 7a and 7b) the differences between the flushing-times (Lenhart, 1990, and Lenhart & Pohlmann, 1995) and the half-life times are significant. This is caused by the fact that in these boxes the flushing does not only depend on the strength of the flow but also on the structure of the flow field, which is not taken into account in the flushing-time approach.

To get an impression of the influence of the underlying hydrodynamic forcing in Fig. 7a and b the distribution of matter after the half-life time is shown for the ICES-Boxes 4 and 6b. In addition the corresponding surface currents integrated over the period of the half-life time are shown. The situations selected are those with the shortest half-life time for box 4 and the longest one for box 6b. Fig. 7a gives the results for box 4 after one half-life time beginning at the 1st of January 1991 and ending at the 9th of January 1991 (9 days), figure 7b shows the result for box 6b covering a period from the 1st of January 1987 to the 2nd of May 1987 (122 days).

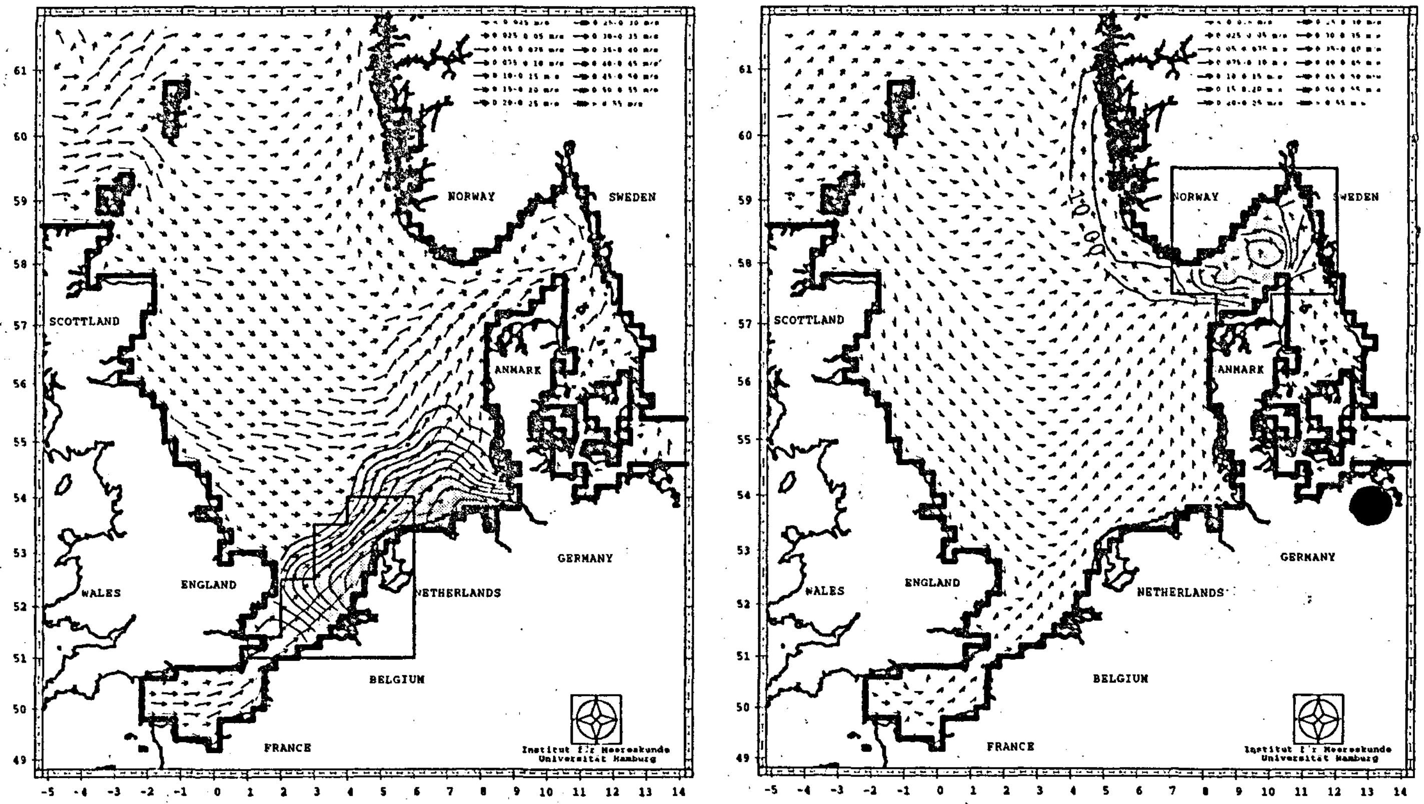

Fig. 7a and b: Distribution of the concentration in percent of the initial values on the surface after one half-life time together with the corresponding currents in m/s for ICES-Box 4 and ICES-Box 6b. In addition the relevant box boundaries are outlined. The contour line interval is 10 percent beginning with 10 percent.

The distribution after one half-life time for box 4 in Fig. 7a demonstrates the mean flow along the coast of the Netherlands deep into the German Bight. The maximum concentration at the surface exhibiting values up to 80 percent is located to the west of the Weser estuary and in the adjacent shallow waters, while the maximum concentration within the box is 70 percent. For this transport of matter the strong current located in front of the coast is responsible. In opposition to these high concentrations Fig. 7b demonstrates the influence of the large volume of box 6a. The concentration at the surface exhibits values up to 60 percent within box 6b and values up to 30 percent in the neighbouring box 6a.

Already by the definition of a half-life time for the water exchange it becomes clear that only one half-life time is not enough time to exchange the water in a box. After a time of *n* half-life times there is still a concentration of $(0.5)^n$ of the initial concentration in the box. The natural deviation (i.e. inter-annual deviation) is of course neglected in this consideration. The problem to define a water exchange time for a natural basin remains.

Conclusions

A three-dimensional dispersion model is used to calculate the half-life times of water exchange in the ICES-Boxes. In the classical approach, the exchange time of water in a box is determined as the ratio of the total mass in the reservoir to the total flux through its boundaries (Bolin & Rhode, 1973) - the flushing-time approach.

Using the half-life time approach it is possible to describe the water exchange in the ICES-Boxes, even when the underlying flow field is inhomogeneous. The results of the calculations show long half-life times with mean values of over 40 days in the mean for the boxes 1, 3a, 4, 5a, 6b, 7a and 7b. With mean half-life times less then 20 days the boxes 3b and 5b are examples for regions dominated by strong homogeneous currents. By looking at the development of the concentration in a box the effect of an increasing concentration depending on the flow field is shown.

The comparison between the half-life times and the flushing-times was carried out, because of missing data calculated by a method similar to the used one. For the boxes with a predominantly homogeneous circulation (1, 2, 3b, 5b and 6a) the differences in the results are insignificant. In the boxes where the circulation is inhomogeneous (3a), where the main circulation influences only a part of the box (5a) or where mesoscale eddy structures are located adjacent to the box boundaries (4, (6b), 7a and 7b), the differences between half-life time and flushing-time approach are not negligible. The results of this method show that in boxes with such a predominantly inhomogeneous flow field the water exchange times are longer than expected up to now.

The advantage of the half-life time approach was demonstrated by an example using the definition of the turn-over time suggested by Prandle (1984). In box 5a (German Bight) the concentration after one turn-over time even exhibits values up to 70 percent particularly in near-coastal regions. Because of the heavy concentration in the box after a turn-over time, the water can not be regarded as exchanged.

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