Meteorologically-induced circulation on the North-West European continental shelf: from a three-dimensional numerical model

A. M. Davies
Institute of Oceanographic Sciences, Bidston Observatory, Birkenhead, Merseyside L 43 7RA, GB,

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ABSTRACT
A three-dimensional hydrodynamic numerical model is used to compute the annual and seasonal meteorologically induced residual circulation on the North West European continental shelf. Meteorologically induced currents are subsequently used to compute turn-over times for various regions of the North Sea. Some of these times are found to be shorter than the three month period over which the meteorological data has been averaged. The usefulness of the concept of a turn-over time in North Sea pollution studies is questioned. It is suggested that wind events on time scales of the order of a few days could be particularly important in determining the rate at which a pollutant is dispersed, particularly a pollutant which resides near the sea surface.


INTRODUCTION
Two-dimensional numerical models have been used extensively over the last 10 years to calculate changes in sea surface elevation produced by tidal and meteorological forces, e.g. see Davies (1976) and Davies and Flather (1978). The emphasis in these models has been the calculation of sea surface elevations, although depth mean currents and hence transports can be computed from them. Pollution problems on the other hand require a detailed knowledge of the depth and horizontal variation of
current, and changes in sea surface elevation are of secondary importance. Using the Galerkin method, Davies (1980a) has developed a numerical modelling method in which a continuous depth variation of current can be computed, information which is particularly important in any pollution problem.

Several authors (Furnes, 1980; Davies, Heaps, 1980; Pingree, Griffiths, 1980) have shown that meteorological effects coupled with variations in bottom topography are important factors which determine the residual circulation of the North Sea and North West European continental shelf.

The models of Furnes (1980) and Davies and Heaps (1980) used idealized bottom topography and a uniform wind stress. The model of Pingree and Griffiths (1980), although incorporating bottom topography, used a uniform wind field. However, in order to be able to examine in detail the meteorologically induced residual circulation on the shelf, and quantify the magnitude and direction of the associated currents, it is necessary to use physically realistic average wind fields. Also meteorologically induced currents in shallow sea areas exhibit considerable vertical shear, giving rise to significant differences in current magnitude and direction through the vertical, necessitating the use of a full three-dimensional model.

In this paper a three-dimensional model incorporating physically realistic bottom topography is applied to the computation of meteorologically induced residual currents over the North West European shelf. Annual and seasonal wind stress data based on observations (Hellerman, 1967/1968) are used to calculate the meteorologically induced circulation on the shelf. However, the model assumes that the sea is homogeneous, which is physically realistic over most of the shelf during the winter periods but not during the summer months when regions of the shelf are stratified. Davies (1981a) has recently shown that the Galerkin method can be extended to take into account stratification in a three-dimensional model. Calculations using stratified models are presently in progress.

In a final section of the paper these meteorologically induced currents are used to compute turnover times for specific areas of the North Sea.

The concept of a turnover time $\tau$ (Bolin, Rodhe, 1973) for a sea area is particularly important in pollution problems. The turnover time $\tau$ is defined by:

$$\tau = \frac{M}{F},$$

where $M$ is the total mass of water in the sea area, and $F$ is the total flux of mass leaving per unit time.

In the steady state, when the total mass, fluxes and internal processes within a sea area are independent of time, the turnover time is equivalent to the residence time or average transit time, and is the mean time water particles have been in the sea area at the moment they are leaving it (Bolin, Rodhe, 1973). In the sea a true steady state is never achieved, however in a numerical model such a state can be readily obtained.

Although $\tau$ will depend upon the total flow through an area, it appears appropriate initially to compute values of $\tau$ due to meteorologically induced flow only, since this is particularly important in the North Sea. The object is to gain some insight into the time scales involved.

The finite difference grid of the three-dimensional numerical model used in these calculations is shown in Figure 1. The model has a grid resolution of $1/3^\circ$ latitude by $1/2^\circ$ longitude, and a staggered finite difference scheme is used in the horizontal. With this grid, surface elevation ($\z$), is computed at the centre of the grid square, the north-south component of current ($V$), at the northern and southern sides of the square, and the west-east component of current ($U$), at the western and eastern sides. Using such a grid, the flux through a particular area can be readily computed, provided the boundaries of the area coincide with the grid lines used in the model.

For the purpose of computing the turnover time of the various regions of the North Sea, a division into seven areas has been made (see Fig. 1). This division is of course arbitrary, but is chosen to agree as closely as possible with the ICES division (Otto, 1977) of the North Sea (Fig. 2). Slight differences in the boundaries of the various areas, arose because the ICES regions did not coincide with the finite difference grid of the model. Region 7 in the central North Sea is further divided into northern (region 7') and southern (region 7") areas.

To the author's knowledge, no other numerical modelling work aimed specifically at computing $\tau$ values for areas of the North Sea, or of the North Sea as a whole has been performed. Previous numerical calculations which are particularly relevant to the problem of turnover times were performed by Maier-Reimer (1977; 1979). He used a two-dimensional North Sea model to compute the residual circulation induced by the $M_2$-tide and an annual mean wind stress. From this circulation the time taken for a particle of pollutant to leave the North Sea, starting from a particular location was determined.

**NUMERICAL MODEL**

The three-dimensional hydrodynamic equations, neglecting non-linear terms and shear in the horizontal may be written in polar coordinates as:
where \( k \) is the coefficient of bottom friction, taken as constant. Davies and Furnes (1980) found that a value of \( k=0.005 \) was an appropriate value to use in a three-dimensional tidal shelf model.

This value of \( k \) is significantly larger than the value of 0.0025 used in two-dimensional models (Davies, Flather, 1978). However in a two-dimensional model, bottom stress is related to the depth mean current, whereas in the present model it is related to the bottom current. From observations of bottom stress and bottom current values of \( k \) ranging from 0.0043 to 0.006 have been obtained (Davies, Furnes, 1980). Also, Davies (1981 b) using a three-dimensional model with the above formulation of bottom friction and \( k=0.005 \), has accurately simulated the change in current magnitudes and sea surface elevations in the North Sea during a major wind event in April 1976. A value of \( k=0.005 \) therefore appears appropriate to use in both three-dimensional tidal models and surge models.

We now seek a solution of equations (2), (3) and (4) for \( \zeta \), \( U \), \( V \) subject to boundary conditions (5), (6). Expanding the two components of velocity \( U \), \( V \) in terms of \( m \) depth dependent functions \( f_i(z) \) and horizontal-space and time dependent coefficients \( A_i(\chi, \phi, t) \) and \( B_i(\chi, \phi, t) \) gives:

\[
U(\chi, \phi, z, t) = \sum_{i=1}^{m} A_i(\chi, \phi, t) f_i(z),
\]

\[
V(\chi, \phi, z, t) = \sum_{i=1}^{m} B_i(\chi, \phi, t) f_i(z). \tag{8}
\]

Using the Galerkin method in the vertical space domain equations (3) and (4) are multiplied by each basis function \( f_i \), and integrated with respect to \( z \) over the interval 0 to \( h \). By integrating the term involving the vertical eddy viscosity, boundary conditions (5) and (6) can be included (Davies, 1980a), giving:

\[
\int_{0}^{h} \frac{\partial U}{\partial t} f_i dz = 2 \omega \sin \phi \int_{0}^{h} V f_i dz - \frac{g}{R \cos \phi} \int_{0}^{h} \frac{\partial \zeta}{\partial t} f_i dz - \int_{0}^{h} \frac{1}{\rho R \cos \phi} \frac{\partial P}{\partial \phi} f_i dz - f_i(h) k U_h(U_h^2 + V_h^2)^{1/2},
\]

and:

\[
\int_{0}^{h} \frac{\partial V}{\partial t} f_i dz = -2 \omega \sin \phi \int_{0}^{h} U f_i dz - \frac{g}{R \cos \phi} \int_{0}^{h} \frac{\partial \zeta}{\partial t} f_i dz - \int_{0}^{h} \frac{1}{\rho R \cos \phi} \frac{\partial P}{\partial \phi} f_i dz - f_i(h) k V_h(U_h^2 + V_h^2)^{1/2} + \frac{G_s}{\rho} f_i(0) \int_{0}^{h} \frac{\partial V}{\partial z} f_i dz. \tag{10}
\]

It is evident from equations (9) and (10) that the bottom and surface boundary conditions occur in these
equations as products with \( f_r(0) \) and \( f_r(h) \), and therefore if these products are to be non-zero, the \( f_r \) must be chosen such that:

\[
f_r(0) \neq 0 \quad \text{and} \quad f_r(h) \neq 0.
\]

(11)

Turning now to the choice of basis functions \( f_r(z) \). In a series of numerical computations, Davies (1980) has shown that an expansion of 10 cosine functions is sufficient to reproduce the depth variation of current, and has applied such an expansion to the computation of the monthly-mean wind induced circulation of the North West European continental shelf (Davies, 1980 c). An expansion of cosine functions has also been used by Davies and Furnes (1980) in computing \( M_2 \) tidal currents on the shelf. Here again cosine functions are used, with \( f_r \) given by:

\[
f_r = \cos \alpha_r z / h,
\]

(12)

and a suitable choice for \( \alpha_r \) is:

\[
\alpha_r = (r-1) \pi \quad \text{for} \quad r = 1, 2, \ldots, m,
\]

(13)

in which case:

\[
f_r'(0) = 0,
\]

(14)

and:

\[
f_r'(h) = 0,
\]

(15)

where \( f_r' = df_r/dz \). It should be noted that this choice of \( f_r \) also satisfies condition (11).

Davies and Furnes (1980) used a parametrization of eddy viscosity of the form:

\[
N = \frac{K (U^2 + V^2)}{\sigma},
\]

(16)

with \( \sigma = 10^{-4} \) s\(^{-1}\) and \( K = 2.0 \times 10^{-5} \), in computing the \( M_2 \) tide on the shelf. This formulation is used in the present model.

In (16), \( U \) and \( V \) denote depth mean currents given by:

\[
U = \sum_{r=1}^{m} A_r a_r, \quad V = \sum_{r=1}^{m} B_r a_r,
\]

(17)

where

\[
a_r = \frac{1}{h} \int_{0}^{h} f_r dz.
\]

Substituting equation (16) into (9) and (10), and expanding \( U \) and \( V \) in (2), (9) and (10) using expansions (7) and (8) gives a set of coupled partial differential equations involving \( \zeta, A_r \) and \( B_r \) (exact details can be found in Davies, 1980 a, b). These equations can then be integrated forward through time to give the time variations of \( \zeta, A_r, B_r \) over a given sea area produced by changing time and spatial distributions of \( F_s, G_s, \partial P/\partial \chi \) and \( \partial P/\partial \theta \). Currents at any depth can then be calculated from the \( A_r \) and \( B_r \) using expansions (7) and (8). Details of the finite difference grid, and method of time integration used in these calculations is given by Davies (1980 a, b).

Solutions are generated from a state of zero displacement and motion, expressed by:

\[
\zeta = 0; \quad A_r = B_r = 0 \quad \text{at} \quad t = 0 (r = 1, 2, \ldots, m).
\]

(18)

Along a closed boundary the normal component of current is set to zero, for all \( t \geq 0 \), thus:

\[
A_r \cos \psi + B_r \sin \psi = 0 (r = 1, 2, \ldots, m),
\]

(19)

where \( \psi \) denotes the inclination of the normal to the direction of increasing \( \chi \).

Consider now conditions satisfied along the open boundaries. A radiation open boundary condition was applied along the edge of the continental shelf. This condition involves a prescribed relation between total normal component of depth mean current \( q \) and total elevation \( \zeta \) given by:

\[
q = q_t + q_M + \frac{c}{h} (\zeta - \zeta_T - \zeta_M),
\]

(20)

where \( \zeta_M \), the meteorologically induced sea surface elevation, is determined from:

\[
\zeta_M (\chi, \phi, t) = (P - P(\chi, \phi, t))/\rho g,
\]

(21)

where \( P \) is a mean atmospheric pressure taken to be 1012 mbar, and \( P(\chi, \phi, t) \) is the atmospheric pressure at the sea surface at point \( \chi, \phi \) on the model’s open boundary at time \( t \). In equation (20), \( C = (gh)^{1/2} \); the normal component of the current due to meteorological influence \( q_M \) is set to zero, and the tidal part of the normal current \( q_T \) arising from the \( M_2 \) component of the tide is determined from:

\[
q_T = Q_M \cos [\sigma_M, t + V_M - \gamma_M].
\]

(22)

The effect upon the meteorologically induced circulation on the shelf of using the hydrostatic approximation (equation 21) and setting \( q_M = 0 \) at the shelf edge has recently been examined by Davies (1982) using a model extending beyond the shelf edge to 20\°W. He found that the annual mean meteorologically induced circulation on the shelf computed using the extended model was indistinguishable from that computed using the shelf model, with the boundary conditions described above. Although this result justifies the use of these boundary conditions at the shelf edge, it is important to note that Davies and Flather (1978) found that these boundary conditions were not appropriate in a limited area model of the North Sea.

The change in sea surface elevation arising from the \( M_2 \) tide is given by:

\[
\zeta_T = H_M \cos [\sigma_M, t + V_M - \gamma_M].
\]

(23)

In equations (22) and (23), \( \sigma_M \) denotes speed, \( V_M \), the phase of the equilibrium constituent at time \( t = 0 \) at Greenwich, \( Q_M \), the amplitude of the normal component of depth mean \( M_2 \) tidal current, and \( \gamma_M \), the phase of that current. Also, \( H_M \) and \( \gamma_M \) denote amplitude and phase of the \( M_2 \) tidal elevation. The \( M_2 \) tidal terms \( H_M, R_M, Q_M \), and \( \gamma_M \) along the open boundaries of the model were
those derived previously (Flather, 1976) in computing the M2 tide on the continental shelf; based on the observations of Cartwright (1976).

From equation (22) the depth mean current along the open boundaries of the model can be determined. However, in order to close the problem, it is necessary to make an assumption about the contribution of each term in expansions (7) and (8) to this depth mean current. In the absence of any detailed knowledge of the current’s vertical structure along the shelf edge, the assumption was made that only the first term in each expansion contributed to the current at the shelf edge. Consequently along the model’s open boundary,

\[ A_r = B_r = 0 \quad (r = 2, 3, \ldots, m), \quad (24) \]

and from equations (17) and (20) we obtain,

\[ A_1 = \frac{q_U}{q_1}, \quad B_1 = \frac{q_V}{a_1}, \quad (25) \]

where \( q_U \) and \( q_V \) are respectively the U and V components of depth mean current given by (20).

**CALCULATION OF METEOROLOGICALLY INDUCED RESIDUAL CURRENTS AND TURN-OVER TIMES (\( \tau \))**

**Meteorologically induced residual currents**

The seasonal wind stress distributions over the shelf for the four seasons, December/January/February, March/April/May, June/July/August, and September/October/November, at every grid point of the model were interpolated from the wind stress distributions published by Hellerman (1967/1968). The annual mean wind stress was derived in a similar manner from Hellerman’s data. Annual and seasonal atmospheric pressure gradients over the shelf, and distributions of atmospheric pressure along the open boundaries of the model, used in equation (21), were interpolated from pressures given in the Technical Report of the Japanese Meteorological Agency (1968).

In order to determine the meteorologically induced circulation on the shelf, five separate calculations were performed, one for each season, and one using annual meteorological input. In each calculation the model was run from a state of rest to a steady state with M2 tidal input along its open boundaries, and the appropriate meteorological forcing. The pure tidal circulation was also computed, by setting the meteorological forces to zero, and running the model from a state of rest for an identical period of time. By subtracting the tidal solution, from the five solutions obtained with meteorological forcing, the meteorologically induced circulation on the shelf was computed.

Figures 3 to 6 show the meteorologically induced currents (surface, bottom and depth mean) on the shelf for the four seasons.

The convention used to depict currents in these figures, is that the model grid point is indicated by a circle, and the direction of flow is away from this point along the current vector. The length of this vector and the number of vector lines indicates the magnitude of the current.

It is apparent from Figures 3 to 6 that the surface current for each season exhibits a characteristic south-east going flow of water into the North Sea, induced by the predominant westerly winds. The maximum surface current occurs during the winter period (December/January/February), when the wind stress is a maximum, with the minimum in the summer (June/July/August), the period of minimum wind stress.

Depth mean currents for all seasons, show an influx of water into the North Sea, between the north of Scotland and the Shetland Islands. Part of this water mass moves due eastward towards the Norwegian coast, and then flows to the south east along the western edge of the Norwegian Trench into the Skagerrak. The remainder of the water flows southward along the east coast of England. At approximately the latitude of Aberdeen this water mass bifurcates, with some water flowing due eastward into the Skagerrak, and the remainder continuing to the south-east. This south-easterly flow produces a rise in water levels in the German Bight, which in the steady state, balances the imposed wind stress and pressure gradients. A northerly flow of water out of the German Bight, along the west coast of Denmark, driven by the north-south gradient of sea surface elevation, produced by the rise in water levels in the German Bight is evident in each seasonal circulation.

This northerly flow subsequently enters into the Skagerrak along the north coast of Denmark.

At the eastern end of the Skagerrak, water flows into the deep Norwegian Trench, and subsequently leaves the North Sea along the west coast of Norway. Despite the changes in magnitude of currents from season to season, these major features of the North Sea circulation persist throughout. This persistence suggests that the directions of the flow paths within the Northern North Sea are dictated by bottom topography (Fig. 2). The easterly flow at the latitude of Aberdeen, appears to be topographically steered along the 100 m depth contour (Fig. 2) into the Skagerrak. Very little of this water flows across the contours of bottom topography into the Norwegian Trench, before it enters the Skagerrak.

A circulation pattern for the Northern North Sea, corresponding to that described above was postulated by Dooley (1974), based upon observations taken in the North Sea. The fact that Dooley’s circulation pattern from various sets of observations corresponds to that computed with the numerical model, confirms the persistence of the major features of the Northern North Sea’s circulation determined here.

The spatial distributions of bottom currents in the North Sea from season to season also exhibit identical dominant features. In particular, the easterly flow across the Northern North Sea, the flow of water northward out of the German Bight, and the northerly transport within the Norwegian Trench.

For completeness, surface, bottom and depth mean currents induced by the annual mean wind stress and pressure gradients are shown in Figure 7.
Figure 3: Meteorologically induced currents at surface (S), sea bed (B), and depth mean (M) for period December-February.

Figure 4: Meteorologically induced currents at surface (S), sea bed (B), and depth mean (M) for period March-May.
Figure 5: Meteorologically induced currents at surface (S), sea bed (B), and depth mean (M) for period June-August.

Figure 6: Meteorologically induced currents at surface (S), sea bed (B), and depth mean (M) for period September-November.
Calculation of turn-over time:

Although the spatial distributions of the wind induced seasonal circulations show similar patterns, the magnitude of the currents from season to season are different and hence values of $\tau$ for the various North Sea areas will have a seasonal variation. The magnitude of current also changes through depth, and this variation must be taken into account when computing $\tau$ for pollutants which are not uniformly dispersed throughout the water column (e.g., oil, which is mainly confined to the surface layer).

For each area, for the respective seasonal and annual circulations, turn-over times were calculated (a) for the 5 and 10 m surface layers together with the corresponding bottom layers, and (b) for the entire water column from sea surface to sea bed.

The turn-over time for each North Sea area, can be readily computed once the volume of the area, and the flux through it, are known. In the numerical model the surface area and average depth of each grid box are known exactly. Hence the total volume and surface area for a specific sea region can be determined. These volumes together with surface areas, are given in Table 1.

Since the numerical model calculates currents across each side of a grid box, and a continuous current profile through depth, the flux into and out of a particular sea area can be readily computed for any layer of the sea, and for the total depth. In order to calculate the total flux through a layer of fluid, the vertical flux must also be included. Although the vertical velocity is approximately less than one hundredth of the horizontal velocity, the horizontal area of the grid box involved in the flux calculation is large and hence the vertical flux is appreciable. Vertical transport of pollutants is particularly important in coastal regions where downwelling and upwelling occur.

In the steady state the flux into a sea area will balance the flux out of the area exactly. This balance can be used as a check on the accuracy of the numerical calculation, and the extent to which the computed meteorologically induced circulation has reached a true steady state. In the numerical model, the computed flux into and out of each area agreed to better than 0.1%. Slight differences between the flux into and out of an area probably arose because the model had not reached a perfect steady state.

The usual method of computing the total flux through any section is to multiply the approximate depth mean current by the area of the section. If this flux is used to compute the turn-over time, that time may be physically unrealistic in areas where the direction of flow changes from sea surface to sea bed. In that case outward and inward fluxes cancel in their contributions to the depth mean current, and it is impossible to make separate assessments of each for the purpose of calculating turn-over times.

It is evident from Figures 3 to 7 that changes in current direction from sea surface to sea bed do occur over most of the North Sea, particularly in the German Bight. It is therefore necessary to determine at each grid point, the positions within the water column, at which the current reverses, and to compute separately the flux in and the flux out of the column.
Having determined the flux into and the flux out of a particular North Sea area, at each grid point on the boundary of the region, the total flux into and total flux out of the area can be computed by separately summing the individual fluxes. In the steady state the respective fluxes in and out are equal.

Using this method the flux in or out of each North Sea area was computed. From this the turn-over time was determined from equation (1), by dividing the appropriate volumes given in Table 1, by the corresponding fluxes. Since density is constant in the model, mass is replaced by volume, and mass flux by volume flux in equation (1). The turn-over time for the surface and bottom layers can be computed in a similar manner, by computing the layer’s volume from its thickness and surface area (given in Table 1) and dividing by the total flux through the layer. In the case of a layer, the total flux is the sum of the horizontal and vertical fluxes. Care being taken to sum separately the flux into and out of a layer.

In practice this method of computing the turn-over time may give an artificially low value for the case in which the flow meanders across the boundary used to define the area for which the turn-over time is being computed (see Fig. 8).

Figure 8 shows an extreme case in which the flow meanders across the line AD which together with the line AB and the land boundaries, define a region for which the turn-over time is to be computed. In this case the numerical model would yield fluxes \( q_0, q_1 \ldots q_4 \) at current points situated at the centre of each model grid line, computed as described above. If the flux into and out of the area is now computed by summing these individual fluxes (method 1) we obtain:

\[
\begin{align*}
\text{Flux in} &= q_0 + q_2 + q_4, \\
\text{Flux out} &= q_1 + q_3 + q_5.
\end{align*}
\]

If, however, we sum the fluxes along each side of the region before computing the flux into and out of the region (method 2), this gives:

Flux along \( AD = q_0 \),

Flux along \( AB = (q_1 + q_3 + q_5 - q_2 - q_4) \).

Then in this case we obtain:

\[
\begin{align*}
\text{Flux in} &= q_0, \\
\text{Flux out} &= (q_1 + q_3 + q_5 - q_2 - q_4).
\end{align*}
\]

Since in the steady state flux in = flux out, it does not matter which flux we use to compute the turn-over time. Method (1) gives a turn-over time:

\[
\tau_1 = \frac{V}{q_0 + q_2 + q_4},
\]

where \( V \) is the volume of the area, and method (2) gives a turn-over time:

\[
\tau_2 = \frac{V}{q_0}.
\]

Obviously method (1) will give a lower turn-over time than method (2).

For the case in which the current does meander along the boundary of the region, method (1) is probably not physically realistic. This method implies that the pollutant which is in the region ABCD (Fig. 8) is removed by the fluxes \( q_1, q_3 \) and \( q_5 \), and that unpolluted water enters the region through the fluxes \( q_0, q_2 \) and \( q_4 \). In practice, however, it appears reasonable to assume that a large proportion of the pollutant that leaves in flux \( q_1 \), probably returns in flux \( q_2 \), and similarly with \( q_3 \) and \( q_4 \). Consequently the major influx of unpolluted water into the region is produced by the flux \( q_0 \) and it is this flux which has the greatest influence upon the turn-over time. By using method (2), the effect upon the computed turn-over time of a current meandering along a straight boundary is removed, and only a truly external flux of water into the region is used to compute the turn-over time.

Turn-over times in days determined using an annual mean wind stress, computed with method (1) are given in Table 2, and, for comparison, times computed with method (2) are presented in Table 3.

In Tables 2 and 3 the column headed “Surface layer” shows turn-over times for the upper 5 and 10 m of the sea. The “Sea bed layer” refers to the bottom 5 and 10 m. The column headed “Total volume” gives \( \tau \) for the total water mass contained in the area. Two figures are given in this column, the one headed “2D” refers to \( \tau \) computed using the depth mean current; the one headed “3D” gives \( \tau \) taking into account changes in current direction through the water column. It is apparent from a comparison of these two columns that the “3D” turn-over time is significantly lower than the “2D”, for the reasons stated previously. This difference is particularly important, since a two-dimensional numeri-

Table 1
Volumes and surface areas of North Sea regions used in the calculation of turn-over times.

<table>
<thead>
<tr>
<th>Area</th>
<th>Total volume ((10^{-11} \text{ m}^3))</th>
<th>Surface area ((10^{-11} \text{ m}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.86</td>
<td>0.62</td>
</tr>
<tr>
<td>2</td>
<td>5.33</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>3.68</td>
<td>0.80</td>
</tr>
<tr>
<td>4</td>
<td>1.18</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>0.89</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>12.60</td>
<td>0.68</td>
</tr>
<tr>
<td>7'</td>
<td>6.57</td>
<td>0.98</td>
</tr>
<tr>
<td>7''</td>
<td>2.86</td>
<td>0.74</td>
</tr>
</tbody>
</table>
It is evident from Table 3 and Figures 9, 10 and 11, that the turn-over time for the surface 10 m layer is significantly less than for the bottom 10 m layer, due to the reduction in current magnitude with depth. Although \( \tau \) does vary with the thickness of the layer (i.e. the 5 m surface layer has a shorter \( \tau \) than the 10 m layer, see Table 3) this variation with thickness is small compared with the difference in \( \tau \) between surface and bottom layers. This suggests that a precise knowledge of the thickness of the layer over which a pollutant is dispersed is not as important as knowing where in the water column this layer is situated.

It is clear from Table 3 and Figures 9, 10 and 11 that \( \tau \) exhibits a strong seasonal dependency, reflecting the seasonal variations in the magnitude of the wind stress. Values of \( \tau \) also vary from one area of the North Sea to another. Considering the turn-over time of the total volume, it is evident from Figure 11 that for all seasons, area 1 has the largest value of \( \tau \). It is apparent from Figure 1 that area 1 is situated in the central northern North Sea, a region where current magnitudes are significantly smaller than in other areas (see Fig. 3 to 7).

As shown previously, turn-over times computed using method (1) may be unrealistically low since they include these effects. However, by summing grid point fluxes over the straight line sections which determine the boundaries of each area (method 2) these effects are removed, and turn-over times computed with method (2) may be more physically realistic.

Using method (2), and taking into account changes in current direction through the water column, seasonal turn-over times have been computed for the upper 10 m layer of the sea (Fig. 9), the 10 m layer near the sea bed (Fig. 10), and the total water column (Fig. 11 (note differences in scale used in these figures)).
As Figure 10, but for the total water depth.

Also the volume of area 1 is larger than many other areas of the North Sea (see Table 1). This combination of large volume, with small currents, explains the large \( \tau \) value for area 1. Area 5, however, has the shortest \( \tau \), due to its small volume (Table 1), and higher currents (Fig. 3 to 7).

CONCLUDING REMARKS

The persistence of the major spatial features of the North Sea circulation from season to season is particularly interesting and reflects the dominance of the westerly wind component in each seasonal wind field, and also the influence of bottom topography.

The change in direction and magnitude of the meteorologically induced currents through depth, illustrates the importance of using a three-dimensional model to study wind induced circulation on the shelf. Besides the meteorologically induced residual circulation, there are also the tidal residual currents. The present model does not contain the non linear advective terms and therefore cannot be used to study the tidal residuals. However, a three-dimensional model containing these terms has been developed and the tidal residuals computed (Davies, 1982).

The short turn-over time (of the order of days, see Table 3) for the surface layer, clearly shows that it is the magnitude of the wind stress on a daily, and not a seasonal basis, which will determine how long it takes a pollutant in the surface layer to leave a particular sea area. Also from Table 3 and Figures 9, 10 and 11, it is evident that particularly in the winter, the turn-over time for some areas, even for the bottom layer, can be shorter than the 3 month period over which the wind stresses have been averaged. This demonstrates that changes in wind stress on a shorter time scale than 3 months can determine how long a pollutant remains in a given area.

In this paper turn-over times have been computed using only the meteorologically induced residual currents. Obviously the turn-over time would be modified if tidal residuals are incorporated into the calculation and density effects which are important in the summer are included in the model. However the values of turn-over time given in the table and figures clearly show its dependence upon the magnitude of the meteorological forcing. For this reason it is doubtful whether turn-over times of North Sea areas (even if they include tidal residuals and density effects) are applicable in pollution problems, since the wind field over the North Sea, particularly in winter time, changes on a time scale of three to five days, associated with depressions moving from Iceland to Scandinavia.

Pollution problems however can be usefully studied using the type of three-dimensional model described here and in Davies (1982). Such a model, with the inclusion of density, and driven with a realistic input of tidal and meteorological data could be used in pollution studies.

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