CHAPTER TWO HUNDRED SIX

EFFLUENT DISPERSAL IN EUROPEAN COASTAL WATERS

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ABSTRACT

The mixing of dissolved material discharged from the Windscale nuclear re-processing plant is examined. The first phase involves a numerical modelling study of large-scale long-term mixing over the entire Continental Shelf. The second phase involves a similar modelling study of near-source mixing processes over a region some 100 km square immediately adjacent to the discharge position. In this latter phase, reproduction of instantaneous peak concentrations is required.

The first phase of this simulation has been successfully completed while the second phase is presently being considered. Ironically, it is shown that this second phase poses far more difficult modelling problems and hence the accuracy of simulation attained in the first phase may not be reproduced. The contrasts in these two modelling approaches are examined and their varying complexities explained.

1. INTRODUCTION

The long-term residual circulation of the waters over the European Continental Shelf is of interest for studies such as : the dispersal of pollutants, the dynamics of marine biology and marine chemistry, sediment transport etc. Several numerical models have been formulated to simulate both the tidal and wind-driven dynamics, these models have provided estimates of residual circulation. Some of these estimates are in reasonable agreement as might be expected from the basic similarity in the models. Confidence in such models must be established by verification against actual observed data. However, a preponderence of small-scale variability allied to inadequate instrumental accuracy obstructs direct measurement of the residual circulation.

Since 1963 various substances have been discharged at monitored rates by pipeline into these coastal waters from the nuclear re-processing plant at Windscale (see figure 1). A number of these substances are non-existant in natural form and their introduction is almost exclusively from Windscale. Thus by modelling the mixing processes of such substances and comparing, through time, observed and calculated distributions the validity of the calculated residual circulation can be established. In the present study, Caesium 137 (^{137}Cs) was adopted as a suitable trace material since it remains almost entirely in dilution and with a half-life of 30.1y retains sufficient mass over the time scale of interest.

Regular monitoring of the spread of ^{137}Cs has revealed a net transport northwards out of the Irish Sea, then proceeding in a confined coastal zone around the Scottish Coast into the North Sea. Much of the material then flows in an anti-clockwise gyre southwards along the English coast, eastwards along the Continental coast and finally, some 5 years after the discharge, the material flows northwards along the Norwegian Coast.

The spread of ^{137}Cs may be conveniently partitioned into two phases. The first phase concerns movement over a region approximately 1500 km square embracing the entire Continental Shelf region while the second phase covers movement over a region some 100 km square immediately adjacent to the discharge point. In the first case, the aim was to reproduce mean concentrations averaged over large spatial areas and long time periods while in the second case maximum instantaneous peak concentrations are of concern. (Chatwin and Allen (1985) emphasise the important difference in such requirements). The large scale simulation has been successfully completed (Prandle 1984). Here we summarise the approach used in this simulation and thence outline the related difficulties associated with the near-source simulation.

Perhaps unexpectedly, the near-source problem is shown to be more complex, as a simple illustration of this finding we now examine the relative values of advection and dispersion in mixing processes. The time scale, t_A, for a pollutant to travel a distance L when transported by an advective velocity U is simply L/U. The time scale, t_D, for a pollutant to spread over a region L squared by dispersive processes is L /K where K is the horizontal dispersion coefficient. Thus a rough comparison of the relative effectiveness of these two processes is given by the Peclet Number, P_e where

$$P_e = \frac{t_A}{t_D} = \frac{L/u}{L^2/K} = \frac{K}{Lu} \qquad (1)$$

For values of $P_e << 1$ advection predominates whereas for $P_e >> 1$ dispersion predominates. In the present region residual velocities are of the order of 1cm s^{-1} and $K \simeq 10$ $cm^2 s^{-1}$, hence for distance greater than 100 km from the source advection predominates whereas for distances less than 1 km dispersion predominates. Thus we immediately see that the near-source problem is likely to be more complex since both mixing processes are equally important.

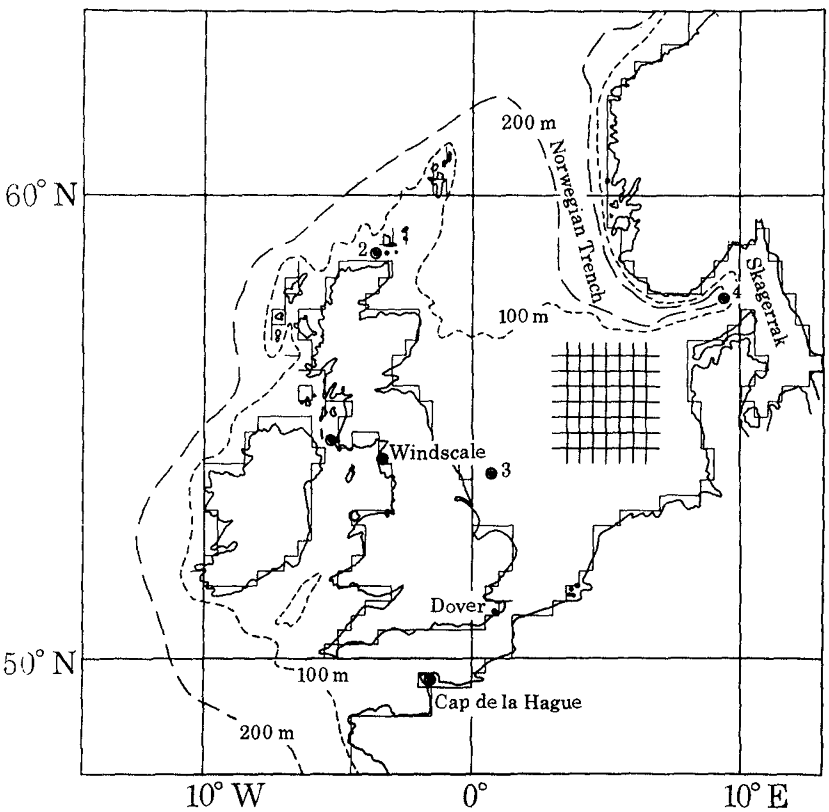

Figure 1.
Extent of the numerical model of the European Continental Shelf.

2. HYDRODYNAMIC MODEL OF THE CONTINENTAL SHELF

The boundaries of the numerical model extend over the complete region shown in figure 1. The location of these open-boundaries in deep oceanic waters beyond the Shelf Edge allowed two important assumptions to be introduced into the prescription of external boundary conditions.

(i) Variations in mean sea level or any attendant residual flow in the ocean can be neglected since numerical simulations show that the Shelf is effectively isolated from such residual forcing terms.

(ii) The concentration of ^{137}Cs was set to zero, reflecting the near-infinite sink capacity of the deep ocean.

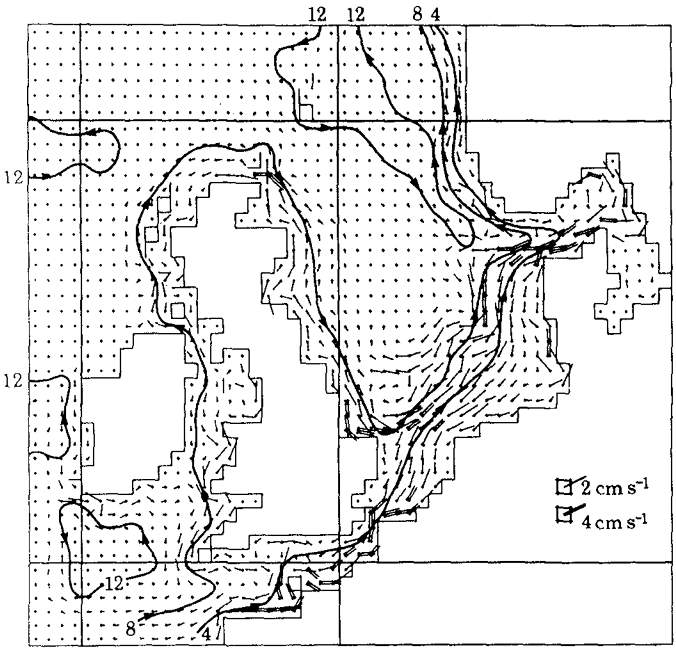

Figure 2.

Residual tidal flow, streamlines in 10^4 m^3 s^{-1}.

Tidal forcing, emanating from the North Atlantic, is the major energy source driving the Shelf Seas. Moreover, within this tidal forcing, the single lunar semi-diurnal constituent M_2 predominates to an extent that in most locations the amplitude of M_2 is greater than the sum of all other constituent amplitudes. These two characteristics permit the following assumptions to be made in the large-scale long-term simulation.

(i) the net tidal residual may be approximated by the M_2 residual

(ii) the equations of motion for wind-driven and density-driven flows may be linearised using coefficients derived simply from the M_2 tide.

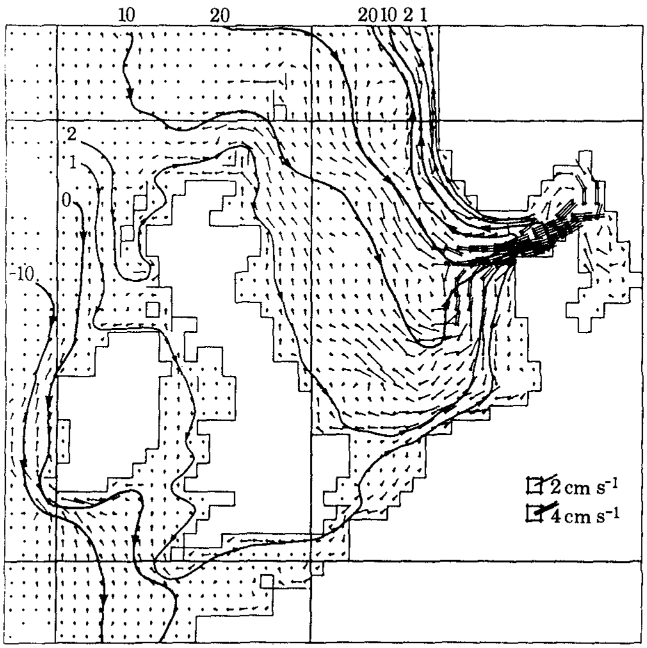

Figure 3.
Response to a westerly wind (mean stress of 0.529 dyn cm^{-2}), streamlines in 10^4 m^3 s^{-1}.

In consequence of (i) and (ii), the net residual motion at any time can be reasonably approximated by linear superposition. Thus, first we computed the (linear) response to (a) a westerly wind stress of unit magnitude and (b) a southerly wind stress of unit magnitude. Then for any specific period we simply add to the tidal residual the results from (a) multiplied by the relevant westerly wind stress and likewise for (b).

Limitation of computer capacity (even using a Cray machine) dictated the use of a vertically-averaged numerical model. Some allowance for density-driven residuals was made by including longitudinal density gradients. However, in general these were shown to be small except for certain localised regions and hence this forcing term was neglected in subsequent simulations.

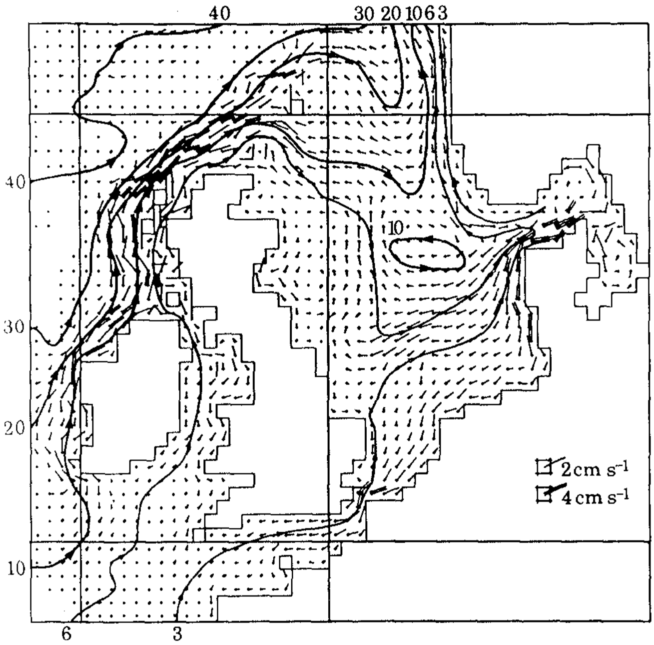

Figure 4.

Response to a southerly wind (mean stress of 0.435 dyn cm^{-2}), streamlines in 10^4 m^3 s^{-1}.

Figure 2 shows the M_2 tidal residual flow, figures 3 and 4 the residual flows corresponding to the long-term mean wind stress from the west and south respectively. In obtaining these results it is important to recognise the reliance on earlier work namely :

(i) oceanic tidal measurements made by Cartwright et al. (1980)

(ii) modelling of North Atlantic tides by Flather, IOS Bidston - to be published

(iii) evaluation of appropriate long-term wind stress data (Thompson et al. 1983)

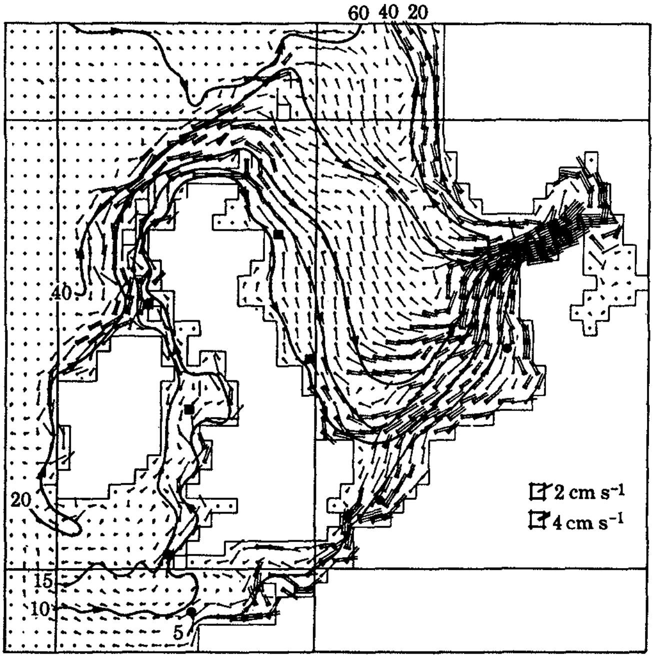

Figure 5.

Net residual flow (tide + winds), streamlines in $10^4\ m^3\ s^{-1}$.

Early confidence in the results shown in figures 2 to 4 was established by comparison with (a) related modelling studies and (b) indirect observational data. With residual currents of typically 1 or 2 cm s^{-1} superimposed on to tidal currents often exceeding 100 cm s^{-1} it is difficult to obtain reliable observational data using existing current meters. However, the validity of the net residual flow pattern (figure 5) was finally established by comparing the computed mean sea level variations (which coincide with the residual flow distributions) with the observed variations in m.s.l. deduced by Rossiter (1967). The close agreement illustrated in figure 6 provided the necessary confidence in the hydrodynamic model to proceed to the development of a mixing model.

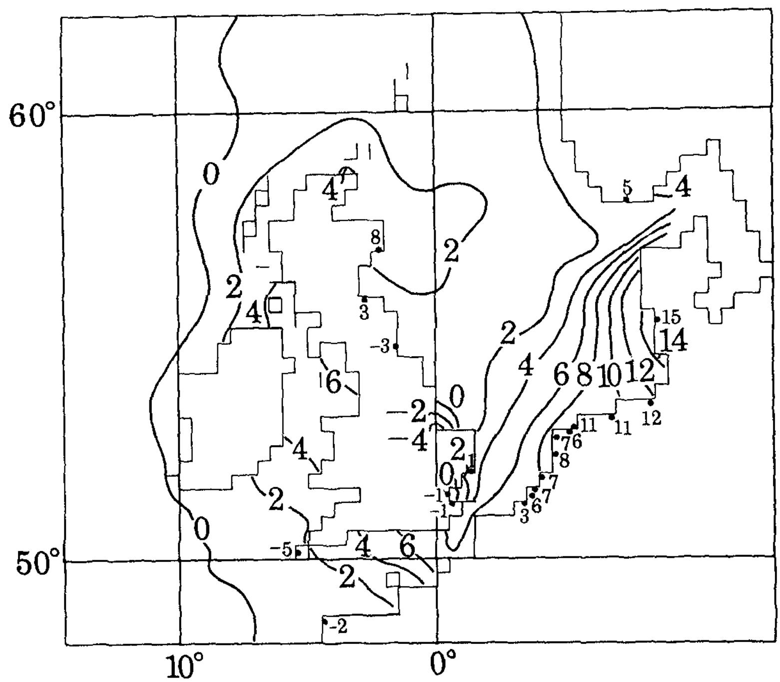

Figure 6.

Mean sea level variation (tide + winds) in cm, $\overset{8}{\bullet}$ observed value from Rossiter (1967).

3. MIXING MODEL OF THE CONTINENTAL SHELF

Tides represent a well-ordered spectrally narrow phenomenon and thus their propagation is more amenable to numerical simulation than mixing processes which occur over a much wider spectral range and involve random processes.

3.1 Numerical dispersion

A low-order difference scheme was used, this scheme introduces additional numerical dispersion such that the dispersion coefficient K is increased by δK given by (Roache 1976)

$$\delta K = \tfrac{1}{2}\,(u\,\Delta x - u^2 \Delta t) \qquad (2)$$

Since stability requires $\Delta x/\Delta t > u$, in most cases $\delta K \rightarrow \tfrac{1}{2} u\,\Delta x$. The model grid size Δx = 35 km and hence to keep $\delta K < K$ ($\simeq 5 \times 10^6 cm^2 s^{-1}$) required $U < 3\ cm\ s^{-1}$. Thus to avoid excessive numerical dispersion it was necessary to drive the mixing model using only the residual flow field. Dispersion due to oscillatory tidal motions was introduced by defining the dispersion coefficients K_x and K_y in terms of the M_2 tidal current amplitudes $\hat{U}$ and $\hat{V}$ (along orthogonal x and y axes respectively) as follows :

$$K_x = 1000\,\hat{u}\,(\hat{u}^2+\hat{v}^2)^{1/2} \quad \text{and} \quad K_y = 1000\,\hat{v}\,(\hat{u}^2+\hat{v}^2)^{1/2}\ (cm^2 s^{-1}) \qquad (3)$$

The inclusion of only residual motions yielded the advantage of enabling a time step of Δt = 12h (from $\Delta t < \Delta x/u$) to be used in the mixing model, whereas simulation of oscillatory tidal motion would require $\Delta t \simeq 0.5$h.

3.2 Model evaluation

Discharges of ^{137}Cs from Windscale started in 1963 with the major discharges occurring in the decade 1970 to 1980. Discharges from other sources may be neglected in comparison with Windscale. Using wind stress data from this period from Thompson (1983). Figure 7 indicates observed and computed concentrations over the Shelf for May 1983 and August 1979. In view of the many simplifications and approximations inherent in the modelling approach, the level of agreement shown was judged to be highly satisfactory.

Sensitivity tests were carried out setting (i) $K_x = K_y = 0$ and (ii) increasing both K_x and K_y by a factor of 5. The computed concentrations showed significant changes in both cases thus indicating that the level of agreement illustrated in figure 7 was a consequence of accurate specification of K_x and K_y. Similar sensitivity tests were carried out setting wind stress values to zero, these tests indicated that good reproduction of ^{137}Cs distributions also depended on accurate specification of the wind-induced advective transport. Thus it was shown that correct simulation of the spread of ^{137}Cs depends on accurate reproduction of both advection and dispersion.

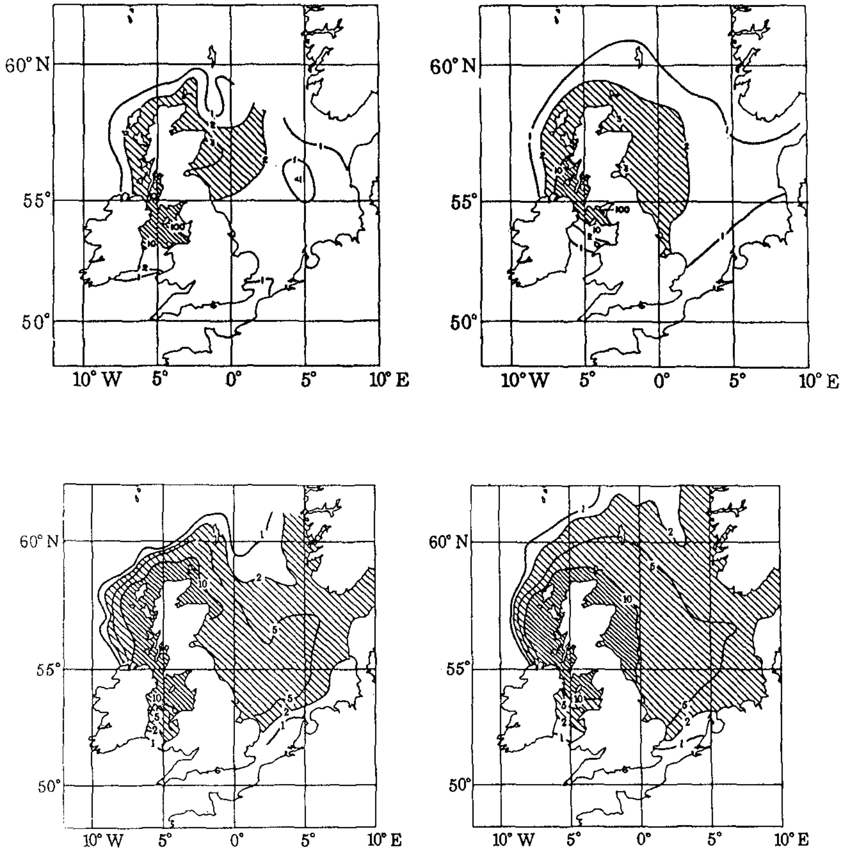

Figure 7.

Observed (left) against computed (right) levels of ^{137}Cs ($pCi\ l^{-1}$) in May 1973 (top) and August 1979 (bottom)

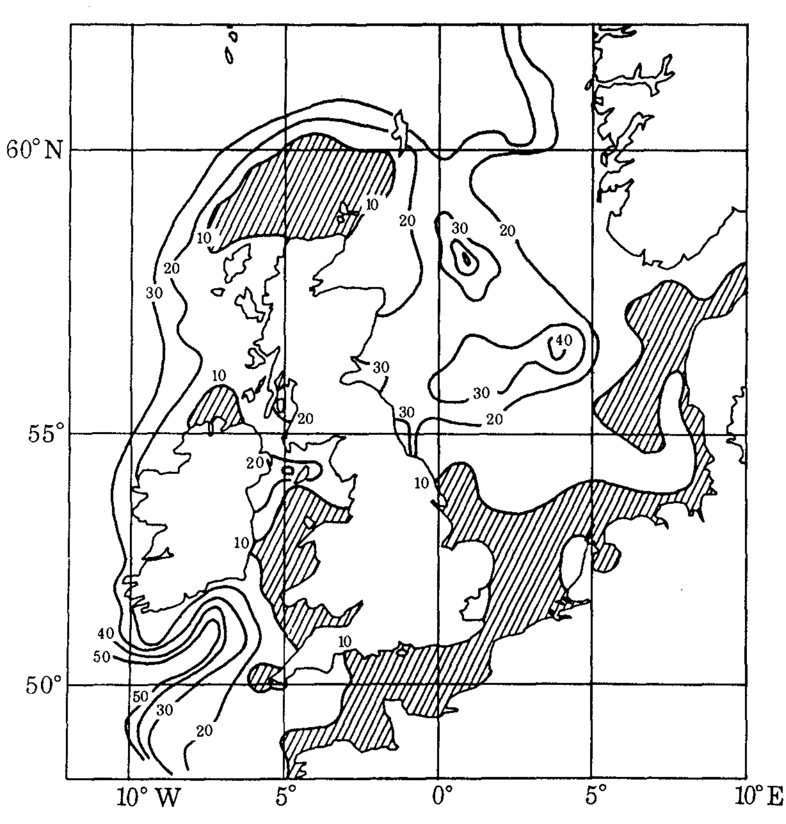

Figure 8.

'Turn-over-times' for model grid-boxes in days, (grid size 20' lat. x 30' long.)

4. MIXING TIME SCALES OF THE CONTINENTAL SHELF

Having validated both the hydrodynamic and mixing models it is useful to calculate pertinent time-scales associated with water quality studies.

Figure 8 shows, T_f, the 'turn-over-time', or 'flushing time' associated with each grid box of the model. The value T_f corresponds to the time taken for the concentration within a grid box to be reduced by a factor $1/e \simeq 0.37$ when all surrounding boxes have an initial zero concentration. The actual values of T_f are a function of grid size, however the variation in values is of interest. In particular, when areas of large T_f (sluggish circulation) lie close to areas of small T_f (vigorous circulation) we might expect to see the formation of thermal fronts at certain seasons.

Figure 9 shows the 'age', T_a of material released from Windscale where T_a represents the average travel time between discharge and arrival at any location. In simple terms, the distribution of T_a is shown to be a combination of radial dispersion from the source modified by the advective transport paths shown earlier.

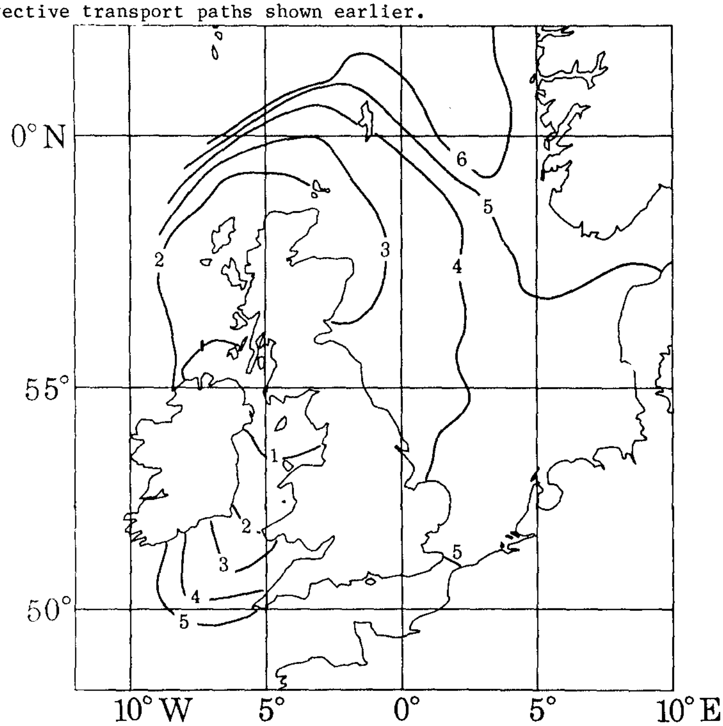

Figure 9. Age (in years) of material discharged from Windscale.

5. SIMULATION OF NEAR-SOURCE MIXING

The interest in localised instantaneous peak concentrations in this region precludes the approach used in the earlier study whereby wind-driven residual flows and tidal residuals were superposed. The requirement to simulate hour by hour motions dictates that real-time surge-tide and tide-tide non-linear interactions must be incorporated (Prandle and Wolf 1978).

In the hydrodynamic section of the model the above requirements mean that boundary conditions must be supplied from an external model dynamically meshed with the 100 km square region of immediate interest. Similarly the specification of concentrations along the boundary of this inner region must involve some real-time simulation of the external region. In both cases, the extent of the meshed external region will be governed by the duration of events to be simulated. For the hydrodynamic model, the speed of propagation of surface gravity waves means that far-distant boundaries are necessary to avoid spurious reflections. However, for the mixing model,lower mass-propagation speeds allow for closer location of external boundaries.

The success of the earlier study suggested that, in most regions, vertical mixing was sufficiently intense to render the problem effectively two-dimensional. Moreover, careful examination of the wind and tidally-driven residual streamlines reveals a close similarity which may be explained by the existence over large areas of a near-geostrophic balance which produces topographic steering of flow along depth contours. Thus, what appears initially to be a three-dimensional mixing problem is effectively reduced to a one-dimensional problem. To a large extent, one- dimensional mixing problems enjoy a self-correcting mechanism whereby an excess of wind-driven advection for one month may be effectively counter-balanced by a corresponding reduction in the next. Unfortunately, the near-source mixing problem is fully three-dimensional with complications including density fronts.

One advantage in the smaller model concerns numerical dispersion. Thus from (2) with a grid size of 1 km and tidal currents less than 50 cm/s, the level of numerical dispersion may be sufficiently contained to allow simulation of tidal oscillatory motions, such simulation is clearly required. If numerical dispersion is found to be troublesome some corrective scheme would have to be employed (see for example Zalesak 1979, Smolarkiewicz 1984).

6. SUMMARY AND CONCLUSIONS

The success of the large-scale long-term simulation of mixing over the Continental Shelf can be attributed to the following :

(i) Siting of open-sea boundaries beyond the Shelf edge thereby providing suitable boundary conditions for both the hydrodynamic and mixing models.

(ii) Predominance of the M_2 tidal constituent, obviating the necessity to consider other tidal constituents and permitting wind-driven residual flow to be linearly superposed.

(iii) Availability of excellent field data including oceanic and coastal tide gauges and comprehensive surveys of ^{137}Cs distributions.

(iv) Strong vertical mixing combined with a near-geostrophic balance for residual flows effectively reduce a 3 dimensional problem to a one-dimensional problem with flow confined to fixed streamlines. Under these conditions a degree of self-correction exists in relation to temporal variations in the advective motions.

The second phase of this study involves a near-source simulation with particular interest in maximum instantaneous concentrations. This study is directly analogous to typical coastal engineering problems involving dispersion from power stations or sewage treatment plants. Unfortunately, none of the above factors apply to this second phase and hence, ironically, a more complex modelling approach is required and the accuracy of simulation is likely to be reduced.

The work described in this paper was funded by the Natural Environment Research Council and by the Ministry of Agriculture, Fisheries and Food.

REFERENCES

CARTWRIGHT D.E., EDDEN A.C., SPENCER R & VASSIE J.M. 1980, The tides of the northeast Atlantic Ocean. Phil.Trans.R.Soc.A , 298, 87-139.

CHATWIN P.C. & ALLEN C.M. 1985, Mathematical models of dispersion in rivers and estuaries. To appear in Vol. 17. Ann. Review of Fluid Mechanics.

PRANDLE D. 1984, A modelling study of the mixing of Cs in the seas of the European Continental Shelf. Phil.Trans.R.Soc.A. , 310, 407-436.

PRANDLE D. & WOLF J. 1978, The interaction of Surge and Tide in the North Sea and River Thames. Geophys.J.R.astr.Soc. 55(1), 203-216.

ROACHE P.J. 1976, Computational Fluid Dynamics. Albuquerque, N.M. Hermosa.

ROSSITER J.R. 1967, An analysis of annual sea level variations in European waters. Geophys.J.R.astr.Soc. 12, 259-299.

SMOLARKIEWICZ P.K. 1984, A fully multidimensional positive definite advection transport algorithm with small implicit diffusion. J.Comp.Phys. 54, (2), 325-362.

THOMPSON K.R., MARSDEN R.F. & WRIGHT D.G. 1983, Estimation of low frequency wind stress fluctuations over the open ocean. J.Phys.Ocean , 13, 1003-1011.

ZALESAK S.T. 1979, Fully multidimensional flux-corrected transport algorithms for fluids. J.Comp.Phys. 31, 335-362.