



**Hydraulics Research**  
Wallingford

PARTICULATE POLLUTANTS IN THE NORTH SEA

- A review of three-dimensional numerical  
models of flow in the North Sea

by

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## ABSTRACT

In October 1988, the water Directorate of the UK Department of the Environment commissioned Hydraulics Research Ltd (HR) to develop a three dimensional model of the Southern North Sea capable of simulating the main processes governing the transport, dispersal and deposition zones of heavy metals adsorbed on to particulate matter which have been discharged into the North Sea. The first stage of the project required a review of previous 3D model of tidal flows and residual currents in the North Sea.

The main purpose of the review was to ensure that the HR model incorporated all the essential physical processes and the grid chosen could resolve the important features of the 3D structure of the flow and density fields.

Work by Davies and Backhaus showed that a 3D model of flow in the North Sea gave residual circulations that did not vary strongly through the depth and agreed approximately with a 2D depth integrated model in the absence of either wind or density variations. Either of these effects gave rise to residual which were substantially different at the surface to those at the bed. Clearly this means that the transport of suspended pollutants in the North Sea in realistic conditions needs to be modelled with a 3D model including the effects of winds and of the density field.

Modelling of the movement of mud in the North Sea in three dimensions has been carried out by Puls using flows taken from the Backhaus model.

Work by James has shown that a 3D model including the evolving density field can simulate the evolution of eddies in the coastal current front.

The ideal 3D model of the North Sea should have horizontal and vertical grid sizes of less than about 5 km and 5-10m respectively to be able to resolve the important features of horizontal and vertical density gradients and the depth varying residual current patterns. The model should also include evolving salinity and temperature fields computed with observed time dependent meteorological forcing - wind, insolation and pressure fields. However it is not practical at present to attempt to combine all these elements into a working model. For example a model with a 5 km grid requires 64 times the processing time of one with a 20 km grid. HR therefore decided to develop two models with uniform grid sizes of 5 km and 20 km. Both models have 10 layers and the option of using a sigma coordinate system. The coarser grid model will be used to simulate longer periods and the finer gridded model will be used to simulate the more detailed residual flows and density fields over shorter periods of time. Both models can simulate evolving temperature and salinity fields.



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## 1. INTRODUCTION

In October 1988 the water Directorate of the UK Department of the Environment commissioned Hydraulics Research Ltd (HR) to develop a three dimensional (3D) model of the Southern North Sea capable of simulating the main processes governing the transport, dispersal and deposition zones of heavy metals adsorbed on to particulate matter which have been discharged into the North Sea. The first stage of the project required a review of previous 3D models of tidal flows and residual currents in the North Sea, which is the subject of this report.

The main purpose of the review was to ensure that the HR model incorporated all the essential physical processes and that the grid chosen could resolve the important features of the 3D structure of the flow and density fields.

The publications of 3D models of the North Sea centre around two groups:

- i) Proudman Oceanographic Laboratory (POL)-work by A M Davies et al (Refs 2, 3, 14).
- ii) University of Hamburg - work by J O Backhaus et al (Refs 4, 5, 19, 22).

These models have been used to produce 3D patterns of residual currents as a basis for predicting the movements of pollutants.

The mixing processes which occur at fronts (areas characterised by steep horizontal gradients of temperature or salinity) in the North Sea have been identified as being important in the dynamics of pollutant transport. I D James (Refs 7, 8.) at POL has been using schematic 3D flow models including an

evolving density field to represent the formation of vortices on a front and how eddies can break off it. This suggests that a 3D model of the North Sea with a grid fine enough to resolve such motions and developing density field should in principle be able to represent these processes.

The important processes of mud transport in the North Sea have been investigated by W Puls (Ref 6) using residual current patterns taken from the 3D flow model of Backhaus. Promising results were obtained.

Work at Delft Hydraulics Laboratory has simulated the dispersion of pollution input at various places in the North Sea. This work is based on a two dimensional (2D) depth integrated flow model and the results need to be treated with caution as the effects of stratification, wind-induced currents and the existence of fronts cannot realistically be taken into account with this methodology. Other pollution transport models based on 2D flow model currents include those of Prandle (Ref 16) and Durance (Ref 17).

Further 3D North Sea flow models are under development at Delft Hydraulics Laboratorium (G Stelling) and Hydraulics Research Ltd.

## 2. MODELLING FLOW IN THE NORTH SEA

### 2.1 A M Davies

In 1983 Alan Davies (Ref 2) described a 3D flow model, with grid size  $1/3^\circ$  latitude by  $1/2^\circ$  longitude, ie approximately 37 km by 27 km, which extended to the shelf edge (Fig. 1). The model solves the tidal flow equations including the wind stress. The equations

are written for a spherical earth. They take the form

$$\frac{\partial \zeta}{\partial t} + \frac{1}{R \cos \phi} \left( \frac{\partial}{\partial x} \int_{-\zeta}^h u \, dz + \frac{\partial}{\partial \phi} \int_{-\zeta}^h v \cos \phi \, dz \right) = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + \frac{u}{R \cos \phi} \frac{\partial u}{\partial x} + \frac{v}{R} \frac{\partial u}{\partial \phi} + w \frac{\partial u}{\partial z} - \frac{uv \tan \phi}{R}$$

$$\frac{-A_H}{R^2} \left[ \frac{1}{\cos^2 \phi} \frac{\partial^2 u}{\partial x^2} - \tan \phi \frac{\partial u}{\partial \phi} + \frac{\partial^2 u}{\partial \phi^2} \right] - 2\omega \sin \phi v \quad (2)$$

$$= \frac{-g}{R \cos \phi} \frac{\partial \zeta}{\partial x} - \frac{1}{\rho R \cos \phi} \frac{\partial P}{\partial x} + \frac{\partial}{\partial z} \left( A_V \frac{\partial u}{\partial z} \right)$$

$$\frac{\partial v}{\partial t} + \frac{u}{R \cos \phi} \frac{\partial v}{\partial x} + \frac{v}{R} \frac{\partial v}{\partial \phi} + w \frac{\partial v}{\partial z} + \frac{u^2 \tan \phi}{R}$$

$$\frac{-A_H}{R^2} \left[ \frac{1}{\cos^2 \phi} \frac{\partial^2 v}{\partial x^2} - \tan \phi \frac{\partial v}{\partial \phi} + \frac{\partial^2 v}{\partial \phi^2} \right] + 2\omega \sin \phi u \quad (3)$$

$$= \frac{-g}{R} \frac{\partial \zeta}{\partial \phi} - \frac{1}{\rho R} \frac{\partial P}{\partial \phi} + \frac{\partial}{\partial z} \left( A_V \frac{\partial v}{\partial z} \right)$$

$$W = \frac{1}{R \cos \phi} \frac{\partial}{\partial x} \int_z^h u \, dz - \frac{\tan \phi}{R} \int_z^h v \, dz + \frac{1}{R} \frac{\partial}{\partial \phi} \int_z^h v \, dz \quad (4)$$

where we denote by

$x, \phi$  east-longitude and latitude, respectively,

$z$  depth below the undisturbed surface,

$t$  time,

$\zeta$  elevation of the sea surface above the undisturbed level,

$P$  atmospheric pressure at the sea surface,

$\rho$  the density of sea water,

$h$  undisturbed depth of water,

$R$  the radius of the Earth,

$\omega$  the angular speed of the Earth's rotation,

$g$  the acceleration due to gravity,

u,v east-going and north-going components of current,  
w vertical component of current,  
 $A_H$  coefficient of horizontal eddy viscosity  
 $A_V$  coefficient of vertical eddy viscosity.

No density variation effects are included in the model.

A Galerkin expansion is used in the vertical, rather than using a finite difference grid. This approach, which consists of the vertical variation being expressed as the sum of a number of continuous basis functions, has the advantage that the resulting velocity distribution is represented as a continuous function of depth rather than being computed at a finite number of levels. It makes it possible to output residual currents at the bed. The vertical eddy viscosity in A Davies' paper is taken to depend on the square of the depth mean current, but its value is independent of the vertical coordinate. The horizontal eddy viscosity is set to a constant value of 100 m<sup>2</sup>/s. The bed friction coefficient k is taken to be 0.005,

$$\tau_b = \rho k u_b^2$$

where

$\tau_b$  bed stress  
 $u_b$  current velocity at the bed.

This value is twice as large as the usual value for 2D models (Ref 21) because it relates to the velocity at the bed rather than the depth mean velocity, and the bed velocity is generally smaller than the velocity higher up.

Davies' model has been calibrated as regards M2 tidal elevations and currents (Ref 14). The mean surface level and residual current for an M2 tide were obtained from the model results. It was found that in the absence of wind the residual current does not vary strongly in the vertical direction so the flow field can be adequately described by a 2D model (see Fig. 2), as long as the variation of tidal current phase and direction in the vertical direction is not of importance. The wind induced circulation computed by inputting the mean annual wind stress (obtained from Ref 13) in each model cell, however, was found to vary substantially in magnitude and direction with depth. It was found to be at least as large as the tidally induced residual current (see Fig. 3). The pattern of currents off the East coast of England shows residuals toward the coast at the bed which may be important in the movement of particulate pollutants.

The conclusion is that a 3D model is needed for realistically simulating residual flows in the North Sea including the influence of the wind.

In 1987, the same model (equipped with sigma coordinates) was used to compute M2 and S2 tides (Ref 3). The resulting chart of M2 tidal amplitude and phase is shown in Figure 4. The idea of the sigma coordinate system is that the vertical coordinate  $z$  is transformed linearly so that the solution domain is between sigma values of zero and one rather than between a moving non flat free surface and a non flat fixed bed. The sigma coordinate transformation is described in detail in Reference 12. The same vertical eddy viscosity was used as before although the model was capable of incorporating an arbitrary vertical viscosity. The results of this model in the form of M2 and S2 elevations and currents were

compared with observations, reasonably good agreement was found. Meteorological effects are not included in this work.

## 2.2 Backhaus et al

Backhaus and Maier-Reimer (Ref 4) use a 3D model of the area shown in Figure 5 with horizontal interfaces. The model does not extend to the shelf edge. The model is described in detail in Reference 19. The grid size is about 22 km (on a spherical grid). The model employs a finite difference grid in the vertical rather than the Galérkin expansion method. There are ten layers with the interfaces at 0, 10, 20, 30, 60, 100, 150, 200, 250, 350 and 700m. This makes it difficult to compute the pattern of residual currents at the bed and such patterns are not presented. The timestep is 20 minutes. The model was run on an M2 tide. The vertical eddy viscosity was set at a uniform value of  $100 \text{ cm}^2/\text{s}$ . The horizontal eddy viscosity was equal to the layer depth  $\times 100 \text{ m/s}$ . This gave a minimum eddy viscosity value of  $1000 \text{ m}^2/\text{s}$ . The bed friction was  $2.5 \times 10^{-3}$ , ie half the value used by Davies but note that the meaning of this coefficient will differ between the models of Backhaus and Davies because of the different ways of representing vertical variation of velocity.

Runs with and without wind forcing are included. Runs with and without density field are shown in Figures 6 and 7. The density field is a prescribed time-independent three dimensional field. The pressure field is computed from the hydrostatic pressure assumption (ie the pressure is equal to the weight of overlying fluid). The effects of the evolution of the salinity and temperature fields are not included.

In the absence of wind the surface residual currents obtained by Backhaus with and without including a density field are shown in Figures 6 and 7. The residual in the homogeneous case resembles that of Davies (Fig. 2) although there are some differences. It should be noted that residual currents can be computed in different ways even for the same current field, so care is needed in comparing different authors' results (see Ref 20, Figs. 8-10).

The effect of including density variations is greatest in the area of the Norwegian coastal current. Even for vertically well mixed winter conditions Backhaus concludes that the residual currents driven by the horizontal density gradients are significant. This means that the results of 2D flow and transport models, which cannot include these residual currents which vary in the vertical direction, need to be treated with care even in vertically well mixed conditions.

In Reference 5, Backhaus and Soetje reiterate the need for a 3D time dependent model of North Sea dynamics. They also emphasise the dangers in describing systems such as the North Sea in terms of mean seasonal values in view of the variability of the observed meteorological conditions. For example, in spring 1974 the circulation was in the opposite direction to the usual condition<sup>f</sup> (Ref 22). However Backhaus did compute a mean seasonal concentration field which is very similar to ones produced by models with mean seasonal winds.

## 2.3 Delft Hydraulics

### Laboratorium 3D model

A 3D tidal model of the North Sea is also under development at Delft. The 3D scheme is based on a splitting method similar to Stelling's schemes, and has been implemented with an ADI solution method, and is therefore suitable for serial machines. Stelling hopes to implement the fully implicit method for this model in the future.

The model will include a sigma grid in the vertical - each layer consists of a proportion of the total water depth rather than being at a fixed level (as Backhaus' model is for example). The implementation of the sigma grid is being done to help remove problems associated with discretised jumps in the bed due to changing depths. This problem can be seen in 2D land boundaries which run at angles other than  $45^\circ$  or along the grid. Discrete changes in the boundary can generate velocities which are inconsistent with the overall flow pattern. These have been found to cause disturbances up to 10 grid points into the model. This is viewed as a highly undesirable and possibly unstable situation in the vertical direction, which the sigma transformation will not generate, as the grid follows the boundary. Another advantage of the sigma transformation is that there is no need for special treatment of the moving surface, and it can simplify drying at land boundaries. However, as the vertical grid is not fixed over time, interpolation methods are required for output.

## 3. MODELLING FRONTS

Tidal mixing in the North Sea may produce changes from well-stratified conditions to well-mixed conditions within a few kilometers. Such frontal regions

represent important physical, chemical and biological boundaries. Fronts may be areas of concentration of pollution because of convergence. They may also cause intense mixing as they produce eddies. The eddies can move away from the front producing large scale mixing.

Pingree and Griffiths (Ref 10) show how a 2D depth integrated flow model with a grid size of about 9 km can be used to predict approximately where these fronts are situated in the North Sea (Fig. 8). This kind of model cannot simulate the fronts but it can give a good idea of which areas have sufficient tidal mixing to be well mixed throughout the year (such as the southern North Sea) and which areas become stratified in summer. Work by Soulsby (Ref 15) in which the bed boundary layer thickness is plotted predicts very similar areas that are always well mixed. Most of the Northern North Sea is stratified in summer with a thermocline between 20m and 40m below the surface. The temperature difference between bed and surface is typically about 7°C. Charts of temperature at different levels in the North Sea for each month are given in Reference 23. The "Flamborough front" lies between the stratified northern and well mixed southern North Sea in summer. It has been found from recent observations that the Flamborough front is observed mainly as a "bottom feature" with little evidence of strong surface density gradients (Ref 18).

A 3D flow model with an evolving density field is required to simulate the fronts and frontal processes. I D James (Refs 7 and 8) has developed such a 3D model to study both a front bounding a coastal current and a front between a stratified area and a vertically well mixed area. The model is run with a schematic bathymetry representative of the

Norwegian coastal current. A grid with a spacing of 5 km is used in order to resolve the Rossby radius of deformation. The model timestep was taken to be 6 minutes. The model was run with a grid of 32 by 32 cells horizontally with 12 layers.

The model solves for the current and for the evolving density field. The equations are first transformed to a sigma grid and the model can include a free surface. A finite difference scheme is used in the vertical direction rather than a Galerkin expansion. A hybrid scheme is used to compute the advection which is based on the flux corrected transport method of Boris and Book (Ref 9) but is somewhat simplified. No explicit tidal diffusivity is included as the model represents mixing by eddies.

The model, in which tides are not simulated, is found to be able to simulate the evolution of eddies in a coastal current front.

#### 4. MODELLING MUD TRANSPORT PROCESSES IN THE NORTH SEA

In order to compute the fate of particulate pollutants in the North Sea it is necessary to have a model of the transport, deposition and erosion of mud.

Walter Puls (Ref 6) has made use of the residual currents and tidal velocities taken from the Backhaus 3D flow model to simulate mud transport in the North Sea. The area covered is smaller than that covered by the flow model (see Fig. 9). The numerical technique used in the mud transport model is a Monte-Carlo tracer method with about 50000 tracer particles. The mud processes simulated include advection by residual currents, diffusion, settling, erosion and deposition.

The horizontal diffusion coefficient is taken to be  $0.1 \text{ m}^2/\text{s}$  and the vertical diffusion is  $5 \times 10^{-3} \text{ m}^2/\text{s}$  in winter and  $10^{-3} \text{ m}^2/\text{s}$  in summer to account for summer stratification. The model is run using daily residual currents taken from the Backhaus model. Four years are simulated representing 1978 and 1979 twice over. The last year is the one compared with observations.

The predicted suspended sediment concentrations are compared with observed values. The gross features are found to be similar. The model computations predict long term deposition in the Norwegian Trough, the Outer Silver Pit and the Fladen Ground. However the author advises caution in interpreting such results in view of the many uncertainties in the physics of mud transport.

## 5. MODELLING POLLUTION TRANSPORT

Work on modelling contaminant movement in the North Sea up to 1986 has been summarised by Taylor (Ref 24). He points to two lines of approach - solutions to the transport diffusion equation in finite difference form and techniques using moving particles. The latter approach removes problems of numerical diffusion (as long as care is taken in interpolating the velocity field). A finite difference technique using first order upstreaming gives diffusion proportional to the flow velocity so the amount of unwanted diffusion is much lower if the simulation makes use of residual velocities (of the order of  $0.1 \text{ m/s}$  or slower) rather than tidal velocities (values greater than  $0.5 \text{ m/s}$ ).

Work by Prandle (Ref 16) using a finite difference model to simulate twenty years of transport of Caesium discharged at Sellafield and Cap de la Hague shows

generally good agreement with observations. The 2D model used three monthly average wind conditions and no variation of wind stress over the area modelled. For such long periods the coarse time resolution of the wind field does not seem to make the result too inaccurate. Caesium is a dissolved substance which can be satisfactorily modelled with a 2D model.

The Delft Hydraulics Laboratory have developed a model for transport processes in the Southern North Sea (Ref 11). They use a vertically integrated 2D flow model with a uniform grid size of 10 km (Fig. 10). Average summer and winter wind conditions are applied to the model. Based on the calculated residual flows a mass transport and water quality model has been used to calculate the transport of various pollutants in the Southern North Sea. Those substances include heavy metals, nutrients and phytoplankton. To model the movement of heavy metals realistically requires a model to simulate the transport processes of mud in the Southern North Sea. Particulate matter tends to settle into and move within the lower layers of the water column.

Clearly the use of a 2D flow model which cannot represent stratification, wind effects, fronts, and density driven residual currents at depth places some limitations on the confidence one can attach to the results from such a model used to compute the movement of particulates.

## 6. EXISTING HR 3D MODEL

Hydraulics Research Ltd have been modelling 3D flows since 1984. The applications of the model have been primarily to cooling water dispersion studies. The model is part of the HR TIDEWAY suite of programs which means that there are standard programs available

to plot results as time histories or contour plots, to process the results in various ways and to produce colour animations.

In application to the North Sea the model will need to be extended to use a spherical grid rather than a Cartesian one. It also uses horizontal interfaces at present (as does Backhaus) but it is being extended to use a sigma coordinates approach.

However the model does include simulation of both the flow of water and the movement of one solute. It should be readily extended to allow calculation of both temperature and salinity. The model uses a mixing length approach to compute the vertical mixing of solute and momentum including damping functions based on the local Richardson number to account for stratification. Constant horizontal eddy viscosity and diffusivity coefficients are assumed. Because the model has been used to predict temperature variations in Lake Trawsfynydd due to both cooling water and meteorological effects the model already can cope with the effects of stochastic wind and solar heat input. In this application a 10 day period was simulated starting from a vertically well mixed state proceeding to a stratified condition due to solar heating and then becoming well mixed again as winds increased. This is physically a similar heating cycle to that occurring in the northern North Sea.

The model makes use of a flux-corrected transport algorithm (Ref 9) in computing the horizontal advection of the density field. This approach has been used so as to advect fronts without diffusing them in cooling water applications.

The model is implemented on the AMT DAP 605 parallel processing computer at Wallingford. The parallelism

is used in order to update up to 4096 water columns simultaneously. An implicit scheme is used in the vertical so that a double sweep (bed to surface and back) is performed. Horizontally explicit differences are used giving a Courant number stability condition.

Mud transport will be modelled using a 3D finite difference model. The effect of stratification on the vertical turbulent diffusion of mud can be included. It should then be possible to model the transport of heavy metals in a similar way to that adopted for the Liverpool Bay model study (Ref 1).

## 7. CONCLUSIONS

Work by Davies and Backhaus showed that a 3D model of flow in the North Sea gave residual circulations that did not vary strongly through the depth and agreed approximately with a 2D depth integrated model in the absence of either wind or density variations. Either of these effects gave rise to residuals which were substantially different at the surface to those at the bed. Clearly this means that the transport of suspended pollutants in the North Sea in realistic conditions needs to be modelled with a 3D model including the effects of winds and of the density field.

Work by James has shown that a 3D model including the evolving density field can simulate the evolution of eddies in a coastal current front. Provided a fine enough grid is used and the transport scheme used is not diffusive.

Modelling of the movement of mud in the North Sea in three dimensions has been carried out by Puls using flows taken from the Backhaus model. Puls computations predicted long term deposition in the

Norwegian Trough, the Outer Silver Pit and Fladen Ground. However he advised caution in interpreting such results in view of the many uncertainties in the physics of mud transport.

The ideal 3D model of the North Sea should have horizontal and vertical grid sizes of less than about 5 km and 5-10m respectively to be able to resolve the important features of horizontal and vertical density gradients and the depth varying residual current patterns. The model should also include evolving salinity and temperature fields computed with observed time dependent meteorological forcing - wind, insolation and pressure fields. However it is not practical at present to attempt to combine all these elements into a working model. For example a model with a 5 km grid requires 64 times the processing time of one with a 20 km grid. HR therefore decided to develop two models with uniform grid sizes of 5 km and 20 km. Both models have 10 layers and the option of using a sigma coordinate system. The coarser grid model will be used to simulate longer periods and the finer gridded model will be used to simulate the more detailed residual flows and density fields over shorter periods of time. Both models can simulate evolving temperature and salinity fields.

The finer gridded model will be used to check the predictions from the coarser model, especially in the English coastal zone.

## 8. ACKNOWLEDGEMENTS

Section 5 includes material from a visit by J M Floyd to Delft Hydraulics Laboratory. We wish to thank the staff of POL and MAFF for useful meetings.

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## FIGURES



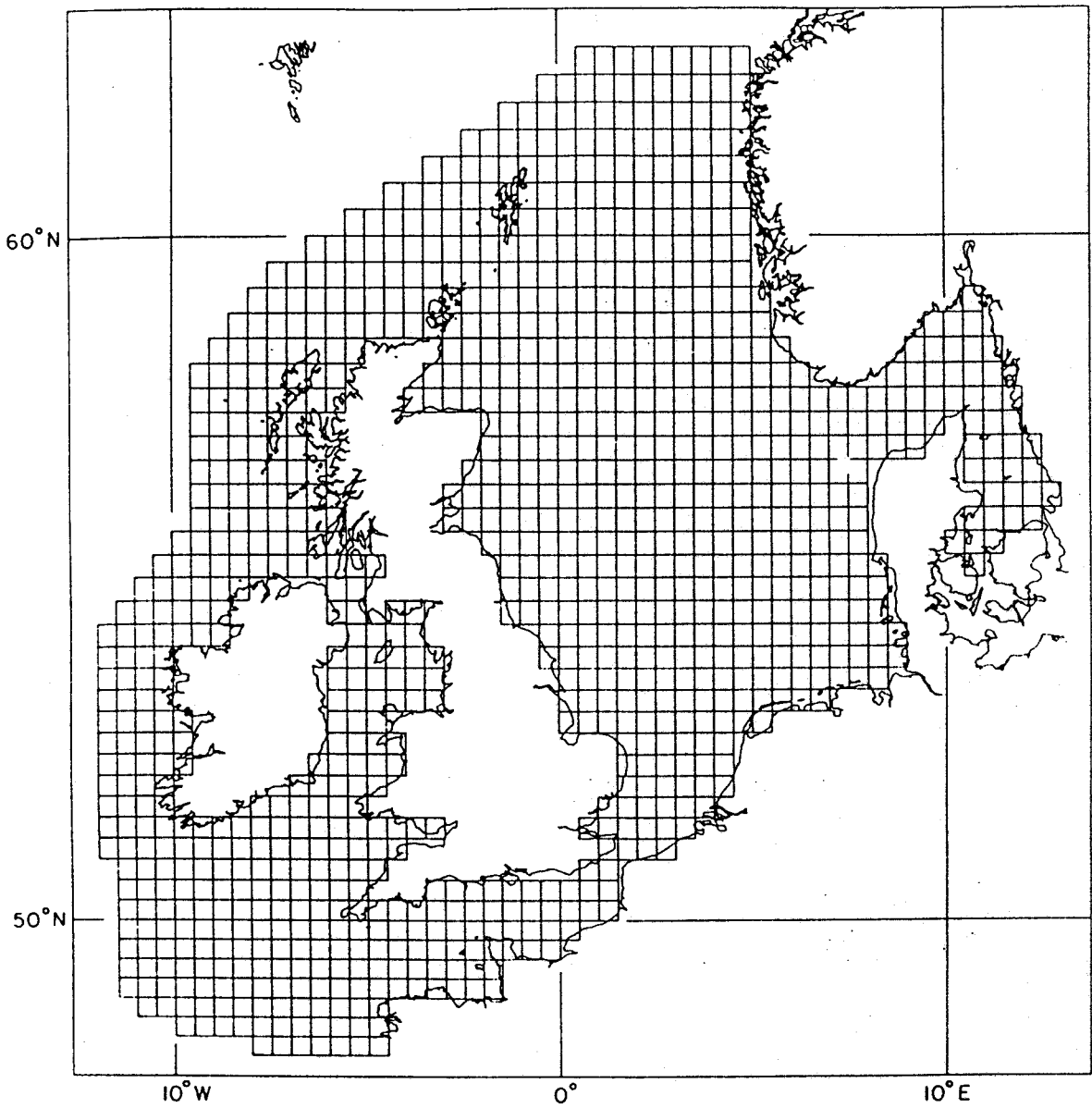


Fig 1 A. Davies model grid (from Ref 2)

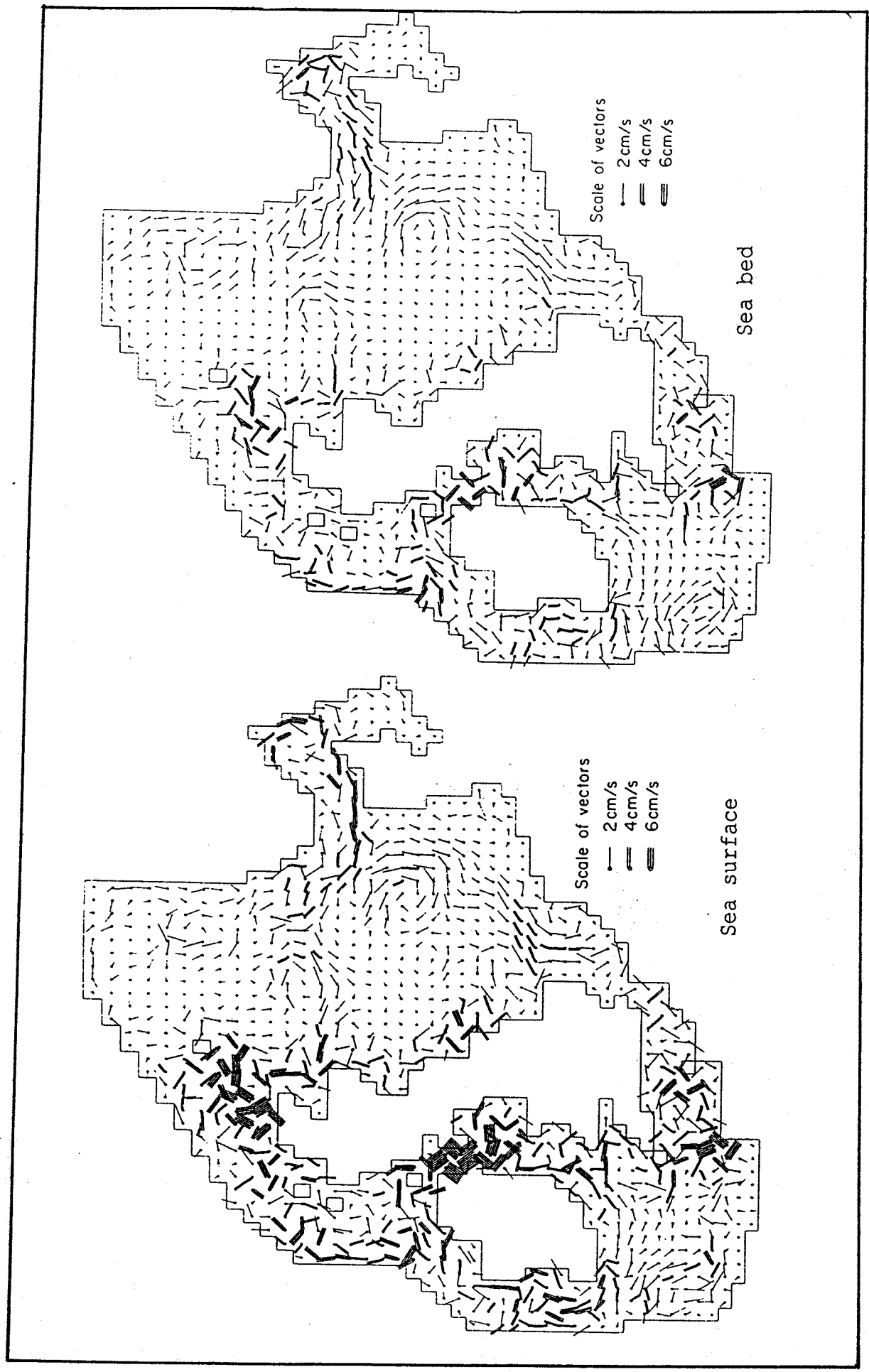


Fig 2 Tidal residual currents (from Ref 2)

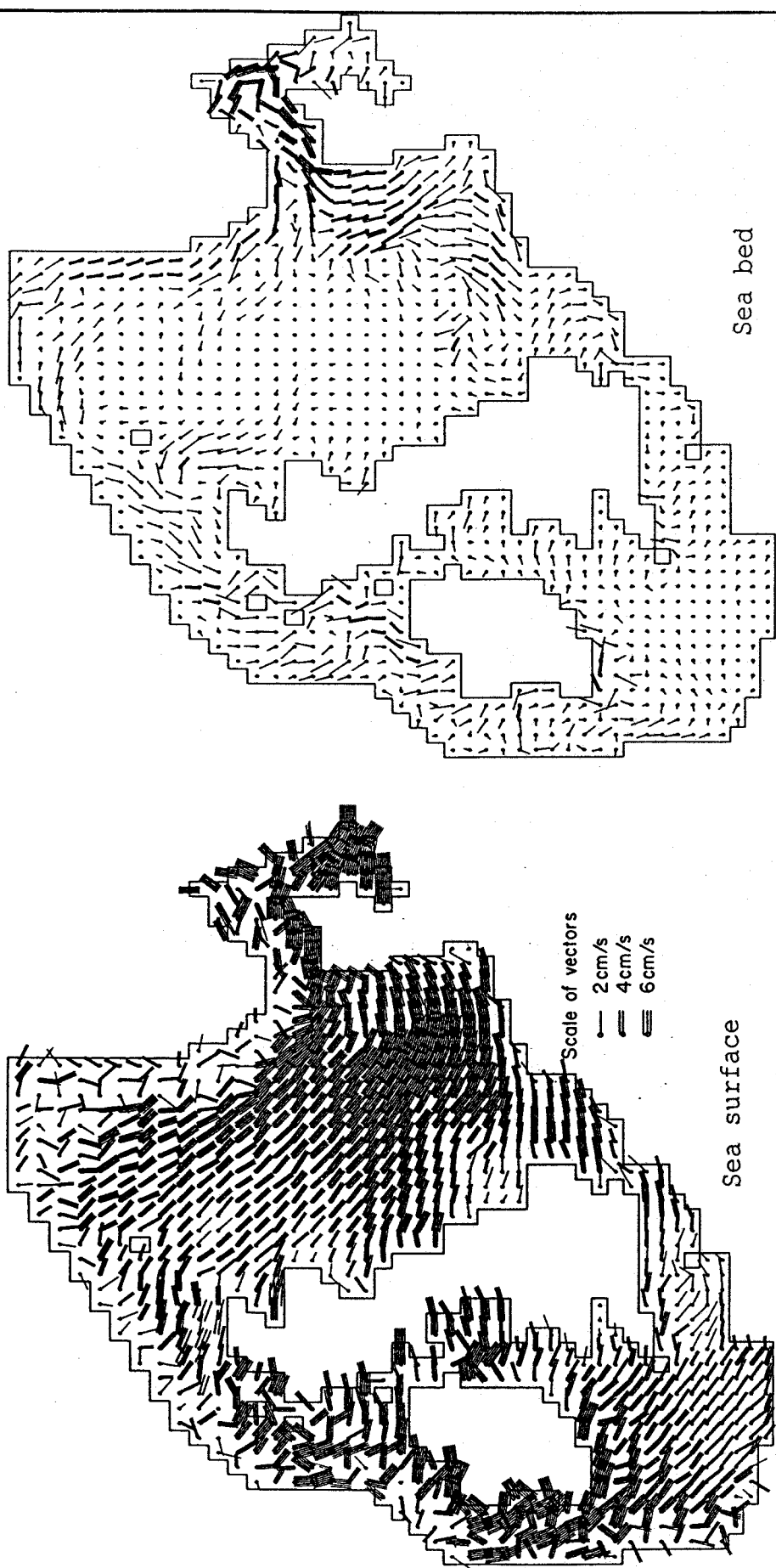


Fig 3 Meteorologically induced residual currents (from Ref 2)

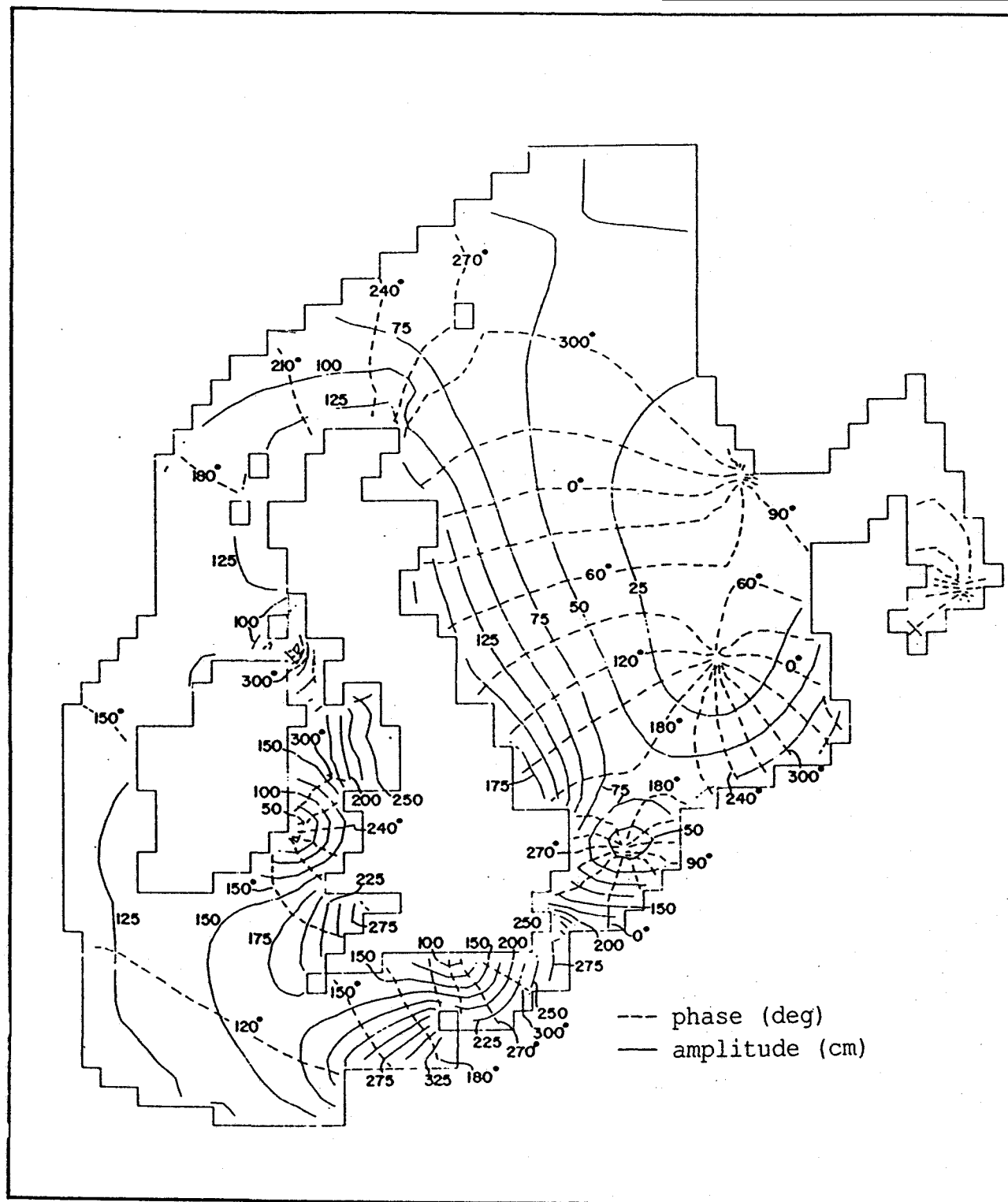


Fig 4 M2 tidal amplitudes and phases  
(from Ref 3)

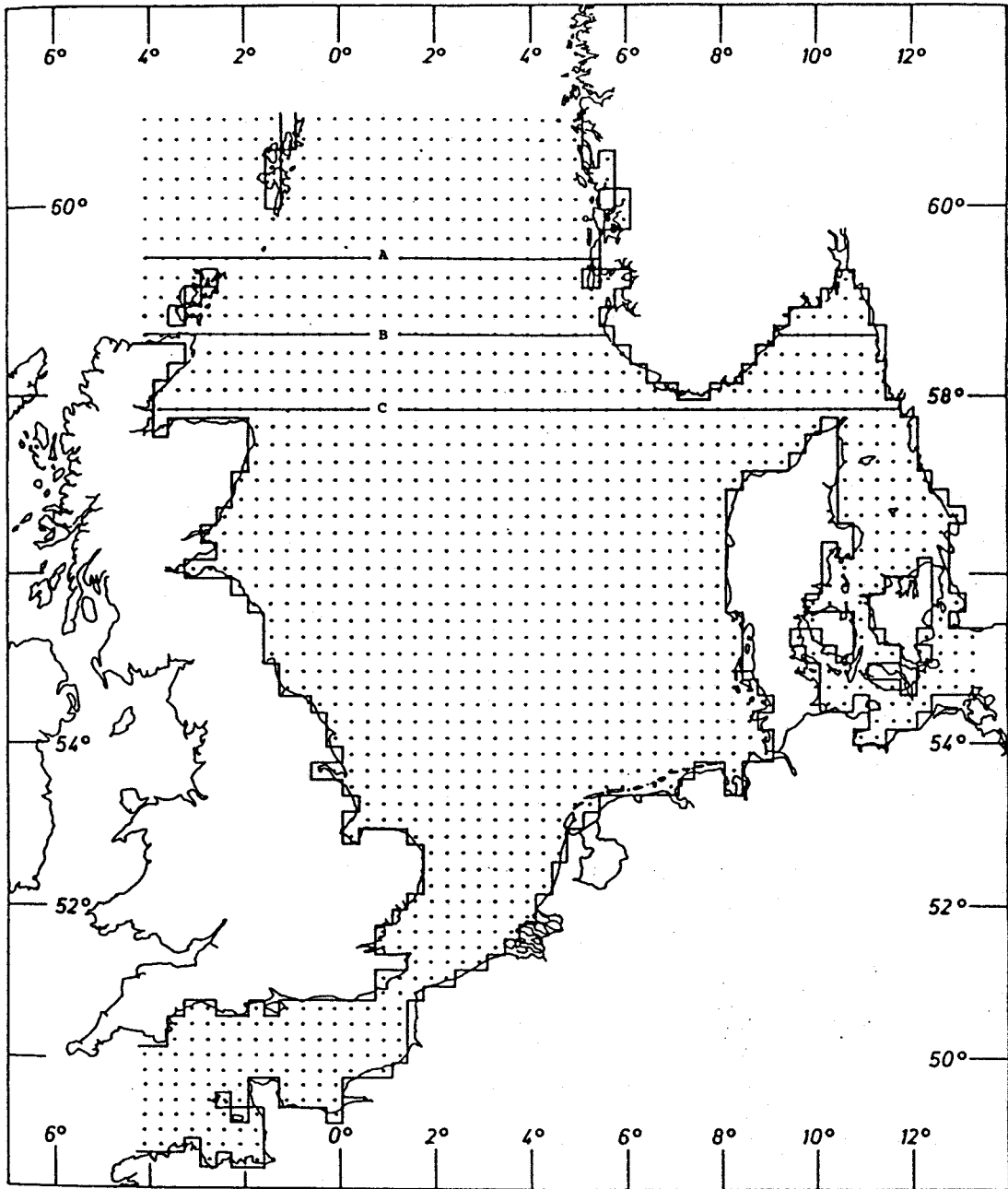


Fig 5 J. Backhaus model grid (from Ref 4)

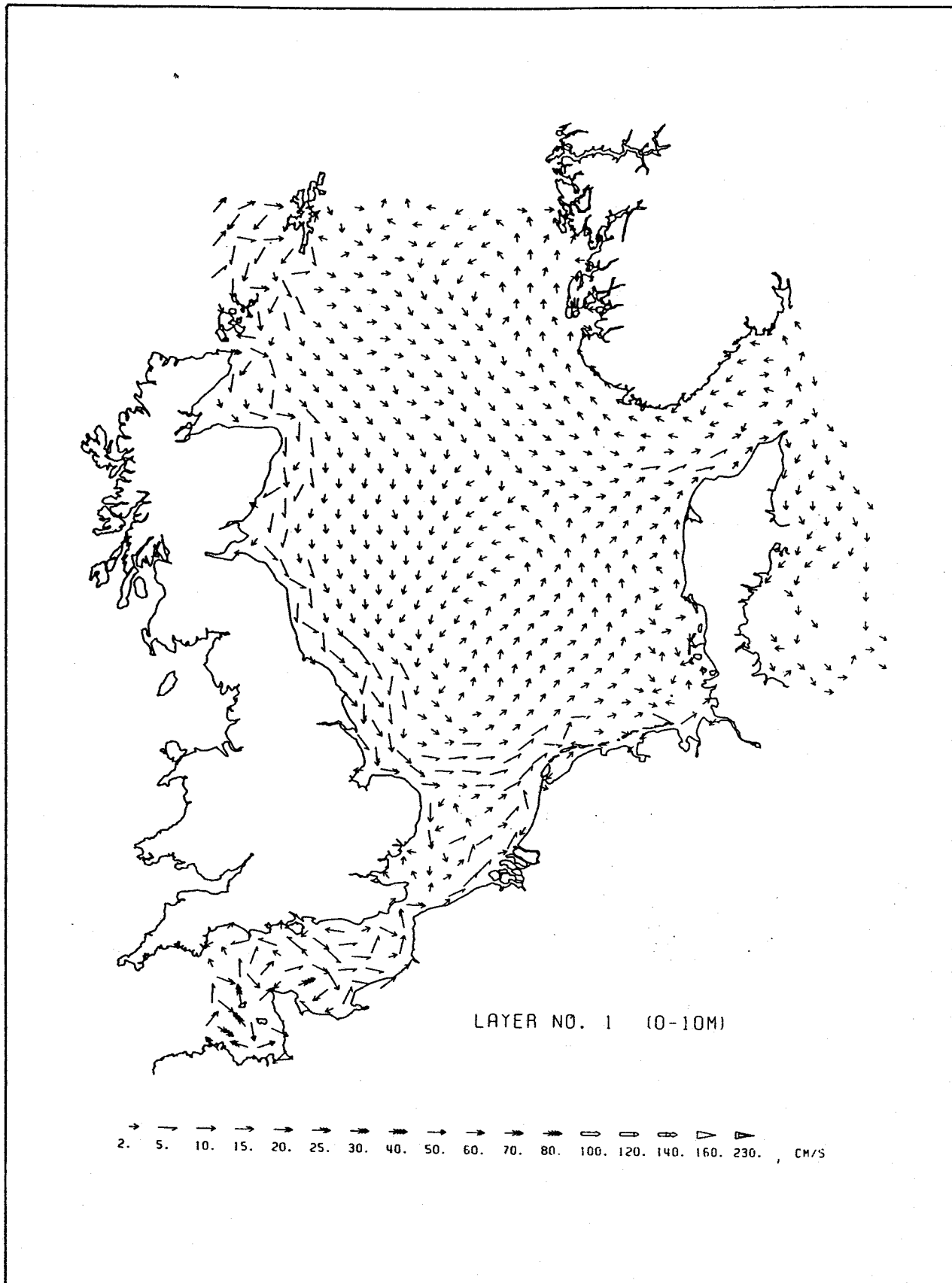
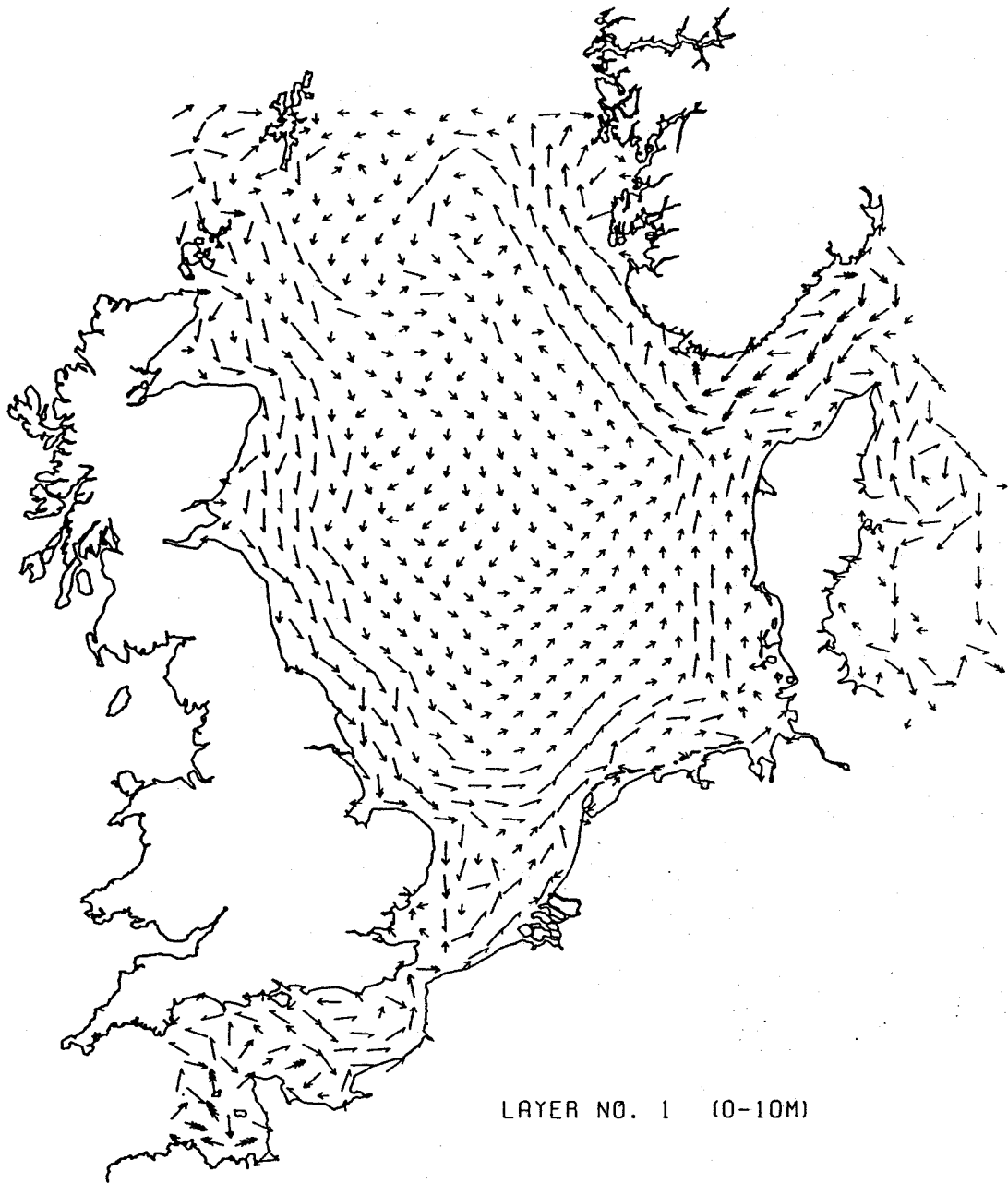


Fig 6 Tidal residual currents (from Ref 4)



LAYER NO. 1 (0-10M)

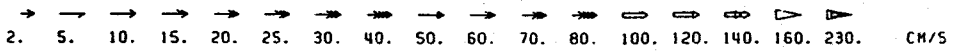


Fig 7 Baroclinic residual currents  
(from Ref 4)

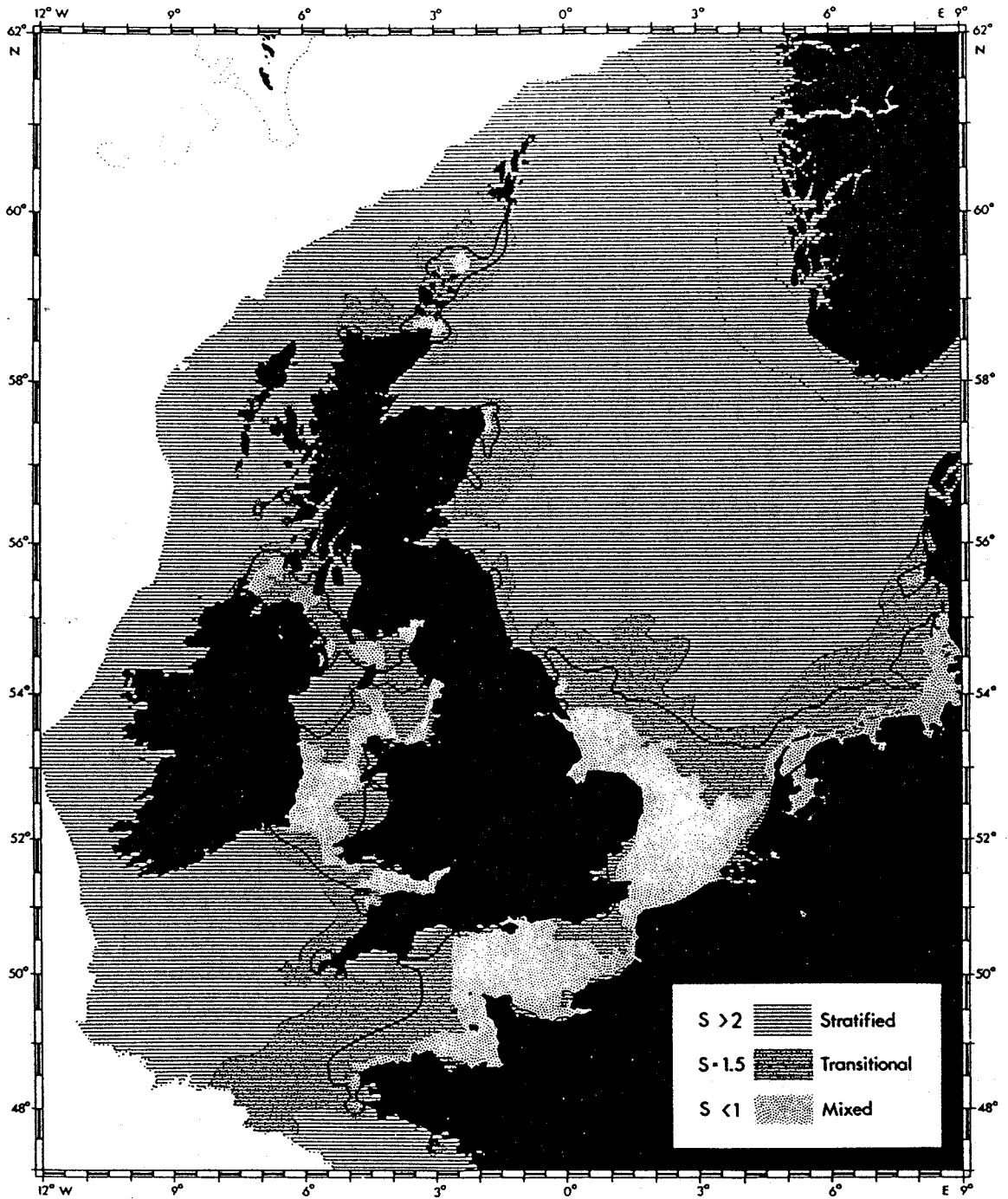


Fig 8 Computed positions of fronts  
(from Ref 10)

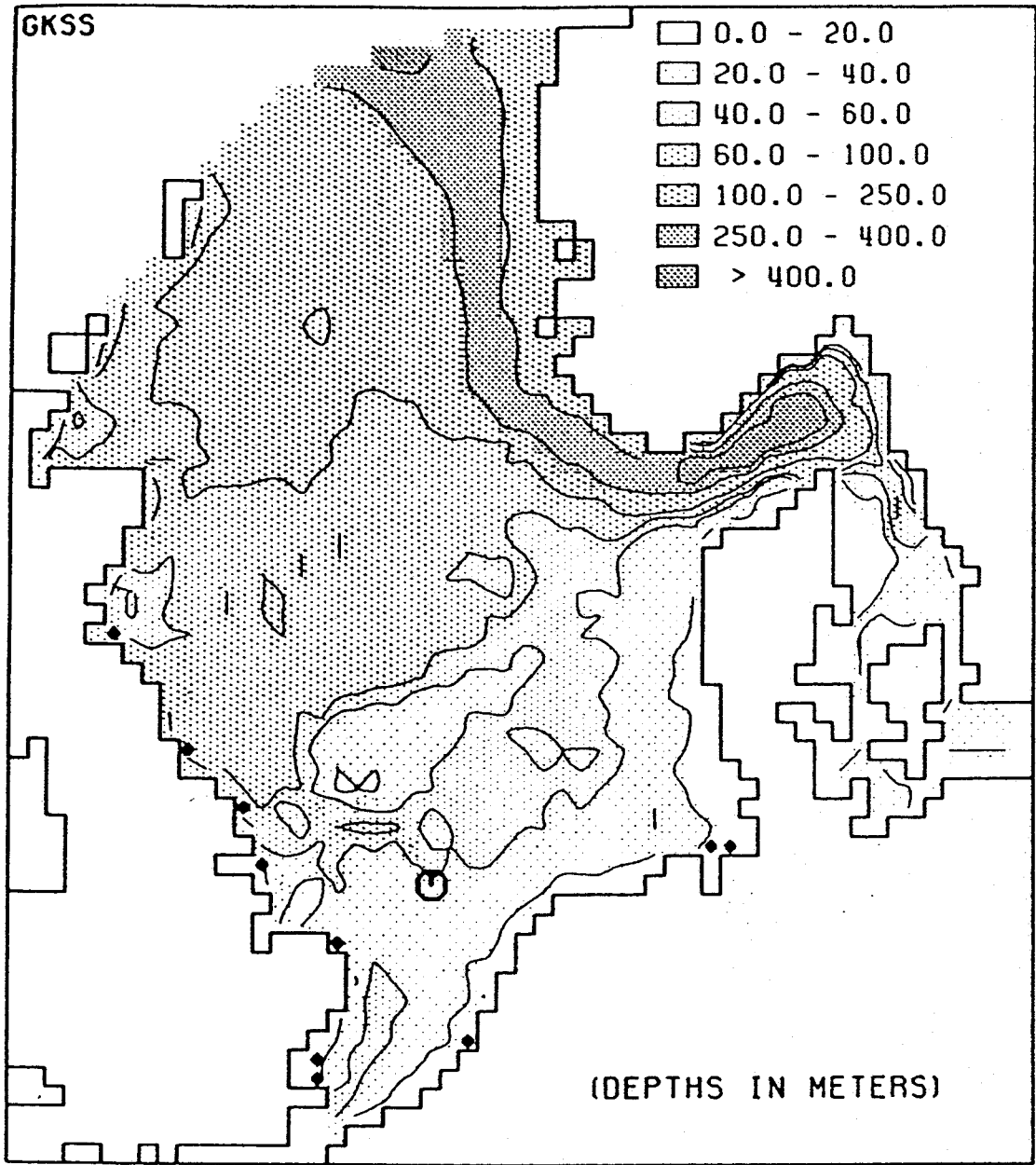


Fig 9 W. Puls model grid (from Ref 6)

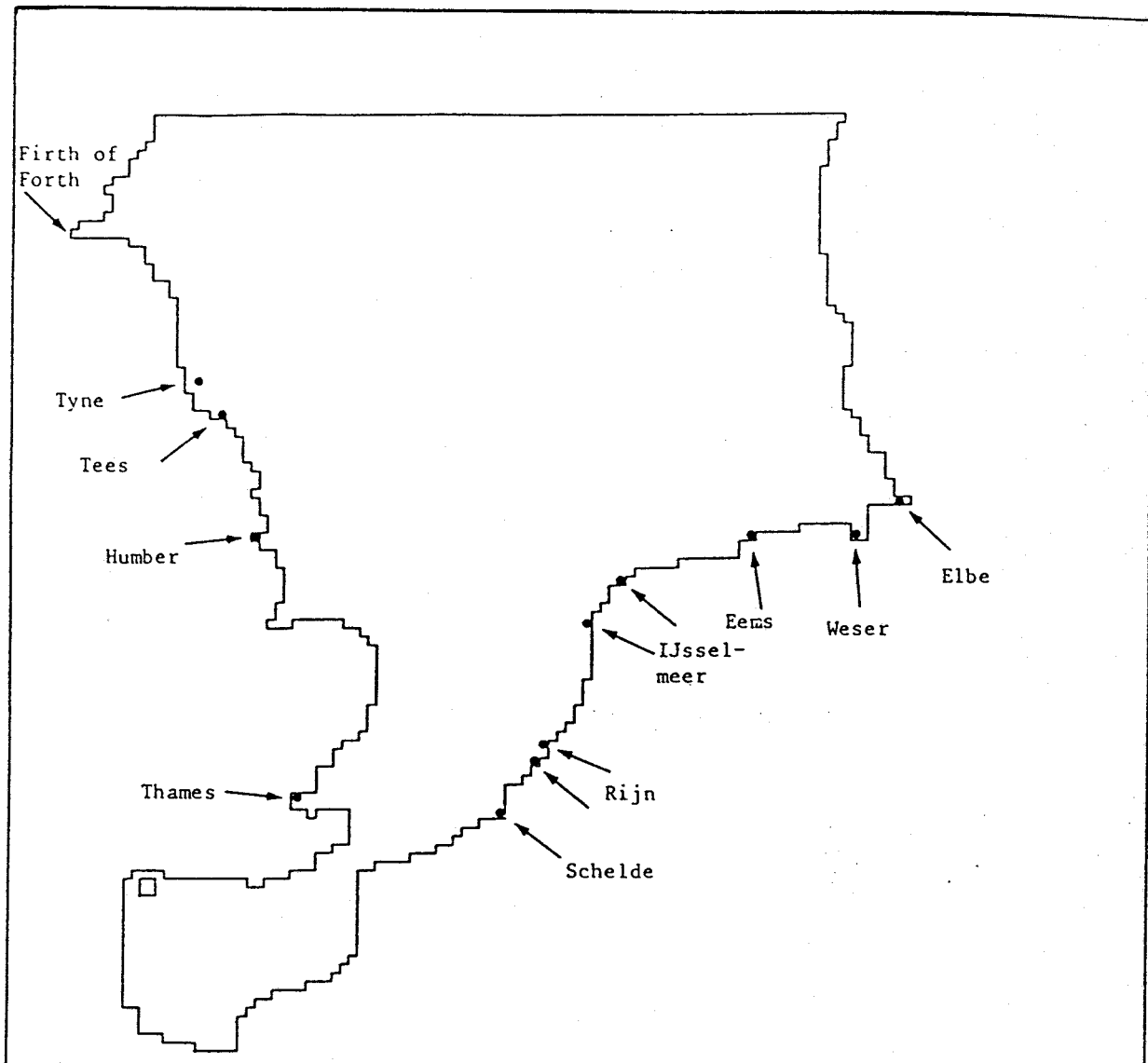


Fig 10 Delft model grid (from Ref 11)