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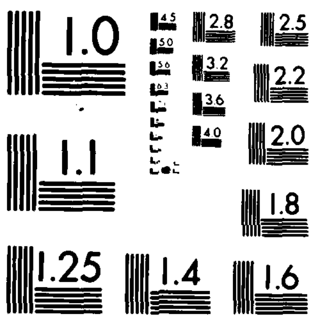

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SACLANT ASW RESEARCH CENTRE MEMORANDUM

A NUMERICAL SCHEME FOR PREDICTING THE LOCATION OF TIDALLY-GENERATED FRONTS IN SHALLOW WATER

by

ALAN J. ELLIOTT

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MAR 19 1980
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1 SEPTEMBER 1979

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6 A NUMERICAL SCHEME FOR PREDICTING THE LOCATION OF TIDALLY-GENERATED FRONTS IN SHALLOW WATER.

by

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This memorandum has been prepared within the SACLANTCEN Underwater Research Division, as part of Project 16.

G.C. Vettori
Division Chief

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A NUMERICAL SCHEME FOR PREDICTING THE LOCATION OF TIDALLY-GENERATED FRONTS IN SHALLOW WATER

by

Alan J. Elliott

ABSTRACT

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A hydrodynamic numerical model is used to compute tidal currents and calculate the parameter $\log_{10}(u^3/h)$, *where* u *is the maximum local tidal speed and* h *is the depth. A recent theory has shown that fronts, marking the boundary between stratified and isothermal water, can be expected to form where this parameter takes a critical value of about 2.2. Thus, if the amplitude and phase of the tidal elevations are known around a region of interest then the likely location of fronts can be predicted if the bottom topography is known. As an example of the method the scheme is applied to the Southwestern Approaches to the English Channel, and good agreement is obtained for the predicted location of a thermal front that has been observed at the western entrance during the summer months. In particular, the model shows that even eastward winds of Beaufort force 8, which occur for at least 10% of the time in this region, are unlikely to influence the location of the front. The computer program and instructions for its use are given in an appendix.*

INTRODUCTION

During recent years there has been a growing body of evidence to suggest that thermal fronts can be generated in shallow water by the bottom-generated turbulence that is associated with tidal currents.

The first observations of this effect were made by Simpson *[1]* who observed a stratified region, persistent throughout the summer months, in the northwestern part of the Irish Sea. This region coincided with a zone characterized for its weak tidal currents, the remainder of the Irish Sea being noted for its strong tidal currents and vertically well-mixed water. In a further investigation *[2]* it was shown that the rate at which work is done by the tidal currents against the bottom friction is proportional to u^3, where u is the tidal velocity, and that the criteria on whether the bottom-generated turbulence will be sufficiently strong to completely mix the water column vertically against buoyancy forces will depend on the ratio of u^3/h, where h is the local bottom depth. By using a numerical model to predict the tidal currents throughout the Irish Sea, and by comparing the contoured values of $\log_{10}(u^3/h)$ with the locations of known fronts, Simpson and Hunter showed that the critical value for the frontal location was around 2.2 (in cgs units).

This work was extended by ~~Fearnhead~~ [3] who used mean tidal charts to construct the contours of the stratification parameter in the waters surrounding the coast of the British Isles. Similar calculations of this kind have also been made by using tidal charts for conditions of mean spring tides and comparing the results with the frontal locations determined from satellite images [4, 5]. In a detailed numerical study of a front observed in the southern Irish Sea, James [6] showed the seasonal development of the frontal system and demonstrated that a front that forms during the neap part of the tidal cycle may not be destroyed during the following spring tide. More recently, Pingree and Griffiths [7] have used a high resolution numerical model to calculate the stratification parameter on the continental shelf around the British Isles, and good agreement was obtained between the predicted and observed frontal locations.

The purpose of this memorandum is to present a readily adapted scheme for making such predictions, and to give (in Appendix A) the listing of a computer program for calculating the stratification parameter $\log_{10}(u^3/h)$.

The advantage of using a hydrodynamic model to compute the tidal streams is that, although a rough estimate of the parameter u^3/h can be made by using tidal charts, this method cannot be used in regions where the tidal currents are not well known. However, in contrast to tidal currents, tidal elevations have been extensively studied for hundreds of years and the details, for almost all regions, can readily be found in the open literature. Taking advantage of this fact, we can use sea level information as input to the hydrodynamic model, i.e. specify the rise and fall of the tide around the boundary, and use the model to calculate the resulting interior tidal currents and the parameter u^3/h in regions where the tidal currents themselves may not be well known.

1 THE HYDRODYNAMIC EQUATIONS

The derivation of the depth-integrated form of the two-dimensional hydrodynamic equations can be found in numerous published papers and standard texts ([8, 9 & 10], for example). However, for completeness, a brief (non-rigorous) account of the derivation is given here. The basic equations are (with the usual notation):

$$\frac{du_1}{dt} + fu_2 = -\frac{1}{\rho}\frac{\partial p}{\partial x_1}$$

$$\frac{du_2}{dt} - fu_1 = -\frac{1}{\rho}\frac{\partial p}{\partial x_2}$$

$$\frac{\partial p}{\partial x_3} = \rho g$$

and

$$\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = 0,$$

where right-handed axes have been chosen, and the z-axis is taken as positive downwards. If we partition each velocity component into a mean and fluctuating part so that

$$u_i = \overline{u_i} + u_i' ,$$

and then take the time average of the equations over an interval that is long compared with the time scale of the fluctuations, we obtain

$$\frac{\partial \overline{u_1}}{\partial t} + \frac{\partial}{\partial x_1}(\overline{u_1' u_1'}) + \frac{\partial}{\partial x_2}(\overline{u_1' u_2'}) + \frac{\partial}{\partial x_3}(\overline{u_1' u_3'}) + f\overline{u_2} = -\frac{1}{\rho}\frac{\partial p}{\partial x_1}$$

and

$$\frac{\partial \overline{u_2}}{\partial t} + \frac{\partial}{\partial x_1}(\overline{u_1' u_2'}) + \frac{\partial}{\partial x_2}(\overline{u_2' u_2'}) + \frac{\partial}{\partial x_3}(\overline{u_2' u_3'}) - f\overline{u_1} = -\frac{1}{\rho}\frac{\partial p}{\partial x_2}$$

(N.B. We have neglected the mean quantity non-linear terms). If we now drop the overbar, and use eddy coefficients to relate the turbulent stresses to the gradients of the mean quantities, then we obtain:

$$\frac{\partial u_1}{\partial t} - \frac{\partial}{\partial x_1}\left(N_1 \frac{\partial u_1}{\partial x_1}\right) - \frac{\partial}{\partial x_2}\left(N_2 \frac{\partial u_1}{\partial x_2}\right) - \frac{\partial}{\partial x_3}\left(N_3 \frac{\partial u_1}{\partial x_3}\right) + fu_2 = -\frac{1}{\rho}\frac{\partial p}{\partial x_1} \qquad \text{[Eq. 1]}$$

and

$$\frac{\partial u_2}{\partial t} - \frac{\partial}{\partial x_1}\left(N_1 \frac{\partial u_2}{\partial x_1}\right) - \frac{\partial}{\partial x_2}\left(N_2 \frac{\partial u_2}{\partial x_2}\right) - \frac{\partial}{\partial x_3}\left(N_3 \frac{\partial u_2}{\partial x_3}\right) - fu_1 = -\frac{1}{\rho}\frac{\partial p}{\partial x_2} \qquad \text{[Eq. 2]}$$

The hydrostatic equation, integrated from the surface ($x_3 = -\eta$) down to a depth x_3 becomes

$$p(x_3) - p_a = \int_{-\eta}^{x_3} \rho\, dx_3' ,$$

and therefore

$$\frac{\partial p}{\partial x_1} = g \frac{\partial}{\partial x_1}\left[\int_{-\eta}^{x_3} \rho\, dx_3'\right] = g \frac{\partial}{\partial x_1}\left[(x_3+\eta)\,\bar{\rho}\right],$$

where

$$\bar{\rho} = \frac{1}{(x_3+\eta)} \int_{-\eta}^{x_3} \rho\, dx_3' ,$$

(we have neglected the horizontal atmospheric pressure gradients). Therefore,

$$\frac{\partial p}{\partial x_1} = g[\frac{\partial}{\partial x_1}(x_3+\eta)\,\bar{\rho} + (x_3+\eta)\frac{\partial \bar{\rho}}{\partial x_1}]$$

$$= g[\frac{\partial \eta}{\partial x_1}\,\bar{\rho} + (x_3+\eta)\frac{\partial \bar{\rho}}{\partial x_1}].$$

Hence,

$$\frac{\partial p}{\partial x_1} = g\bar{\rho}\frac{\partial \eta}{\partial x_1} + g(x_3+\eta)\frac{\partial \bar{\rho}}{\partial x_1},$$

which states that the horizontal pressure gradient has two parts: one part due to the slope of the free surface, and the other part due to the horizontal variations in density.

Hence, the pressure term on the right hand side of Eq. 1 becomes

$$-\frac{1}{\rho}\frac{\partial p}{\partial x_1} = -g\frac{\bar{\rho}}{\rho}\frac{\partial \eta}{\partial x_1} - \frac{g}{\rho}(x_3+\eta)\frac{\partial \bar{\rho}}{\partial x_1} . \qquad \text{[Eq. 3]}$$

The next stage is to integrate the equations vertically and express the variables in terms of depth-mean quantities. For simplicity it will be assumed that the water is well-mixed vertically. Under these circumstances $\rho = \bar{\rho}$ (at all depths) and therefore

$$\int_{-\eta}^{d} [-g\frac{\bar{\rho}}{\rho}\frac{\partial \eta}{\partial x_1}]\,dx_3 = -g\frac{\partial \eta}{\partial x_1}(d+\eta)$$

and

$$-\frac{g}{\rho}\int_{-\eta}^{d} [(x_3+\eta)\frac{\partial \bar{\rho}}{\partial x_1}]\,dx_3 = -\frac{g}{\rho}\frac{(d+\eta)^2}{2}\frac{\partial \bar{\rho}}{\partial x_1} .$$

Consequently, the vertical integration of the pressure terms of Eq. 3 gives

$$-g(d+\eta)\frac{\partial \eta}{\partial x_1} - \frac{g}{\rho}\frac{(d+\eta)^2}{2}\frac{\partial \bar{\rho}}{\partial x_1},$$

with similar terms in the x_2 momentum equation. To integrate the velocity terms over the depth requires the use of kinematic boundary conditions at the top and bottom boundaries.

If $\phi(x_1,x_2,x_3) = 0$ is the equation of the surface and $\underline{u} = (u_1,u_2,u_3)$ is the velocity, then the surface condition is

$$\underline{u} \cdot \underline{\nabla}\phi = -\frac{\partial\eta}{\partial t} . \qquad \text{[Eq. 4]}$$

Since the surface is given by

$$x_3 = -\eta\ (x_1,x_2) ,$$

then

$$\phi(x_1,x_2,x_3) = \eta(x_1,x_2) - x_3$$

and

$$\underline{\nabla}\phi = \left(\frac{\partial\eta}{\partial x_1} , \frac{\partial\eta}{\partial x_2} , -1\right) .$$

Therefore, Eq. 4 gives

$$\frac{\partial\eta}{\partial t} + u_1 \frac{\partial\eta}{\partial x_1} + u_2 \frac{\partial\eta}{\partial x_2} + u_3 = 0 \quad \text{at} \quad x_3 = -\eta . \qquad \text{[Eq. 5]}$$

At the bottom,

$$x_3 = d(x_1,x_2)$$

and

$$\phi(x_1,x_2,x_3) = d(x_1,x_2) - x_3.$$

Therefore $\underline{u}.\underline{\nabla}\phi = 0$ (i.e. no flow through the bottom) gives that

$$u_1 \frac{\partial d}{\partial x_1} + u_2 \frac{\partial d}{\partial x_2} - u_3 = 0 \text{ at } x_3 = d. \qquad \text{[Eq. 6]}$$

If the velocity terms in Eqs. 1 & 2 are now integrated over the depth, and the kinematic conditions of Eqs. 5 & 6 are used, then the momentum equations become (in terms of depth-mean quantities):

$$\begin{aligned} \frac{\partial}{\partial t}[(d+\eta)u_1] = {} & \frac{\partial}{\partial x_1}\left[(d+\eta)\ N \frac{\partial u_1}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[(d+\eta)\ N \frac{\partial u_1}{\partial x_2}\right] \\ & + F_{x_S} - F_{x_B} - f(d+\eta)u_2 \\ & - g(d+\eta)\frac{\partial\eta}{\partial x_1} - \frac{g}{\rho}\frac{(d+\eta)^2}{2}\frac{\partial\rho}{\partial x_1} \end{aligned} \qquad \text{[Eq. 7]}$$

(F_{x_S} and F_{x_B} are the components of the surface and bottom stresses) and

$$\frac{\partial}{\partial t}[(d+\eta)u_2] = \frac{\partial}{\partial x_1}[(d+\eta)\ N\ \frac{\partial u_2}{\partial x_1}] + \frac{\partial}{\partial x_2}[(d+\eta)\ N\ \frac{\partial u_2}{\partial x_2}]$$

$$+ F_{y_S} - F_{y_B} + f(d+\eta)u_1$$

$$-g(d+\eta)\frac{\partial \eta}{\partial x_2} - \frac{g}{\rho}\frac{(d+\eta)^2}{2}\frac{\partial \rho}{\partial x_2}\ . \qquad \text{[Eq. 8]}$$

The final equation that is required is the depth-integrated form of the continuity equation, which will be used to compute the surface elevation. If v is an arbitrary volume of fluid, fixed in space, of density ρ and surface ares A, then

$$\frac{d}{dt}\int_v \rho dv = -\int_A \rho \underline{u}.\underline{ds} + \int_v \delta dv\ ,$$

where δ is the source of fluid/unit volume/unit time.

This gives

$$\int_v [\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \underline{u}) - \delta]\ dv = 0,$$

and hence

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \underline{u}) = \delta.$$

If the flow is assumed to be incompressible, this reduces to

$$\mathrm{div}(\underline{u}) = \frac{\delta}{\rho}\ ,$$

i.e.

$$\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = \frac{\delta}{\rho}\ . \qquad \text{[Eq. 9]}$$

If Eq. 9 is now integrated vertically over the water column and use is made of the kinematic conditions of Eqs. 5 & 6, we obtain

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x_1}[(d+\eta)u_1] + \frac{\partial}{\partial x_2}[(d+\eta)u_2] = (d+\eta)\frac{\delta}{\rho}\ . \qquad \text{[Eq. 10]}$$

This equation, along with the momentum equations 7 and 8, are the ones solved by the numerical scheme. In the present analysis the horizontal density gradient terms in Eqs. 7 & 8 were neglected.

2 FINITE DIFFERENCES

Equations 7, 8, & 10 were solved using centred differences on a regular grid (Fig. 1). (Note that the grid uses left-handed axes; the only effect of this is to change the sign of the coriolis terms in Eqs. 7 & 8). Linear interpolation was used to derive the values of variables required at points other than grid points. A leap-frog scheme was used for the time integration, which involves the storage of three time levels, the time derivatives were evaluated using levels one and three, while the right-hand side of Eqs. 7, 8 & 10 were evaluated at the middle time level. The only exceptions were the diffusive (friction) terms; these were lagged back one time step for reasons of stability.

As an example, the finite difference form of the continuity equation will be derived (the finite difference form of the momentum equations are given in Appendix A). Let

$$\frac{\partial\eta}{\partial t} = (d+\eta)\,\frac{\delta}{\rho} - \frac{\partial}{\partial x_1}\,[(d+\eta)u_1] - \frac{\partial}{\partial x_2}\,[(d+\eta)\;u_2]$$

be written as

$$\frac{\partial\eta}{\partial t} = c_1 + c_2 + c_3,$$

then

$$c_1 = (d+\eta)\,\frac{\delta}{\rho}$$

where δ is the source/unit volume/unit time.

If the quantity δ' is the total source/grid box/unit time then

$$\delta' = (d+\eta)\;(2\Delta x)\;(2\Delta y)\;\delta\;.$$

Therefore

$$c_1 = \frac{(d+\eta)\delta'}{\rho(d+\eta)\;4\Delta x\Delta y} = \frac{\delta'}{4\rho\Delta x\Delta y}\;.$$

Consequently, the finite difference form of this is simply

$$c_1 = \delta'(i,j)\;/\;[(4\Delta x\Delta y)\;\rho(i,j)],\quad TL = 2$$

where $\rho(i,j)$ denotes the value of ρ at the grid coordinate (i,j) and TL = 2 signifies time level 2.

$$c_2 = -\,\frac{\partial}{\partial x_1}\,[(d+\eta)u_1]$$

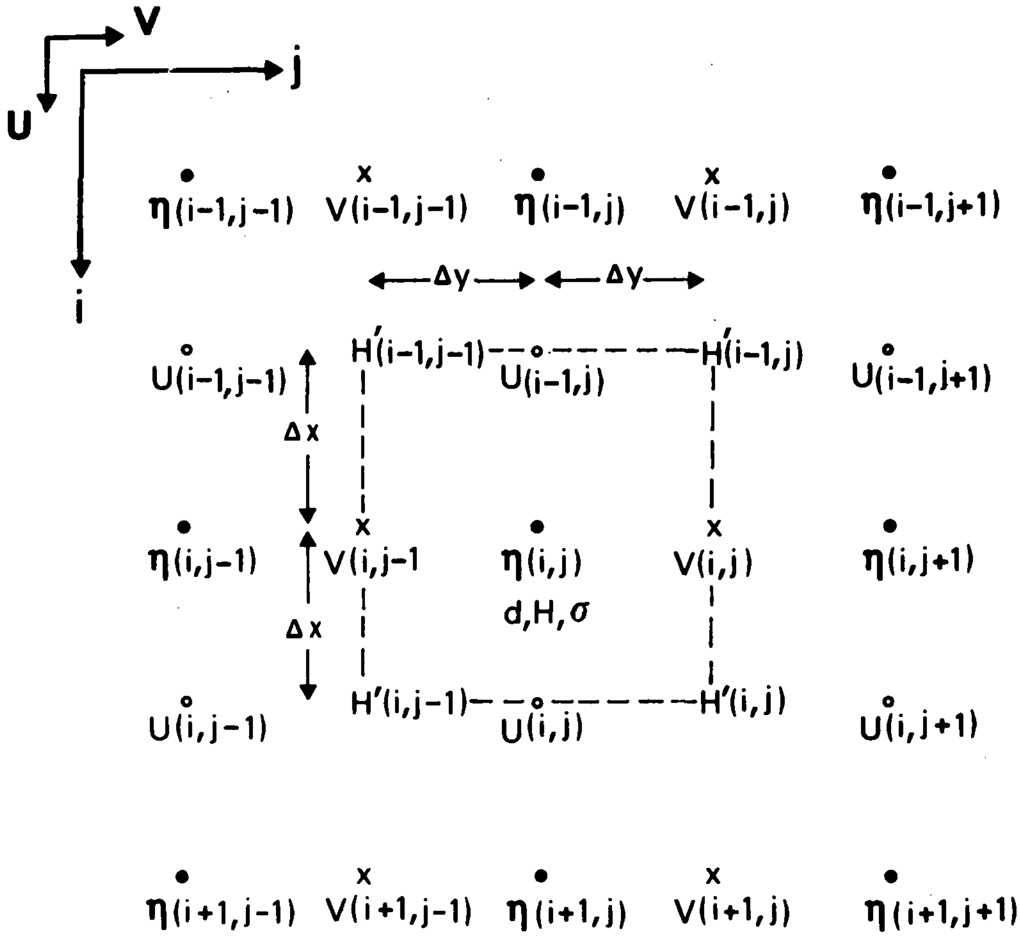


FIG. 1 GRID SCHEME USED IN THE MODEL

Let $(d+\eta) = H$, the total depth, then

$$c_2 = -\frac{\partial}{\partial x_1}[Hu_1]$$

$$= \frac{-\left[\left(\frac{H(i,j) + H(i+1,j)}{2}\right) v(i,j) - \left(\frac{H(i-1,j) + H(i,j)}{2}\right) v(i-1,j)\right]}{2\Delta x}$$

Therefore

$$c_2 = -[(H(i,j) + H(i+1,j))\ v(i,j) - (H(i-1,j) + H(i,j))\ v(i-1,j)] \;/\; (4\Delta x), \quad TL = 2.$$

Similarly,

$$c_3 = [(H(i,j) + H(i,j+1))\ v(i,j) - (H(i,j-1) + H(i,j))\ v(i,j-1)] \;/\; (4\Delta y), \quad TL = 2.$$

Consequently,

$$\frac{\partial\eta}{\partial t} = c_1 + c_2 + c_3$$

becomes

$$\frac{\eta(i,j)|_{TL=3} - \eta(i,j)|_{TL=1}}{2\Delta t} = (c_1 + c_2 + c_3)|_{TL=2}.$$

Therefore,

$$\eta(i,j)|_{TL=3} = \eta(i,j)|_{TL=1} + 2\Delta t(c_1 + c_2 + c_3)|_{TL=2}.$$

This is the equation used to update the surface elevations (see subroutine ETA3 in Appendix A); comparable expressions can be derived in order to update the U and V velocity components (see UVEL and VVEL in Appendix A). In certain circumstances (e.g. when a point lies on or near an open boundary) the full form of the finite difference equations are not used because certain terms are neglected. The points were coded as follows:

For elevation,

(1) outside the computational grid, do not update (i.e. the point lies inland).

(2) a boundary value, specify through a boundary condition.

(3) computational point.

For velocity,

(1) outside the grid or on a solid boundary, do not update.

(2) near an open north-south boundary, nelgect the term involving $\frac{\partial}{\partial x_2}$ and coriolis.

(3) near an open east-west boundary, neglect the term in $\frac{\partial}{\partial x_1}$ and coriolis.

(4) both of the above, i.e. near an open corner of the grid.

(5) normal interior point, update using the full form of the equations.

The finite difference form of the equations were tested by applying the model to simple problems having known solutions. For example, the seiche motion of a rectangular lake, the advance of a wave along a rectangular canal (with and without rotation), the wind-induced set-up of a rectangular bay, and similar problems. In all cases, the difference between the known and computed solutions did not exceed a few percent of the analytical solution. The application of the model to the interpretation of some field observations has been given in a previous memorandum *[11]*, showing a good agreement between the observed and predicted response.

In the present study the amplitude and phase of the surface tide is prescribed around the open boundary of the model. This is a sufficient boundary condition to drive the tidal oscillations (i.e. tidal currents and elevations) in the interior of the model. After allowing at least five tidal cycles for the system to approach a quasi-steady state, the subroutine PARAM (see Appendix A) computes the value of $\log_{10}(u^3/h)$ at each elevation point by averaging the surrounding velocities. At each time step, and for each grid point, the present value of the parameter is compared with the previous maximum and the value is updated if a new maximum has been reached. In this way, the maximum value of $\log_{10}(u^3/h)$ is calculated at every computational elevation point.

3 APPLICATION TO THE SOUTHWESTERN APPROACHES TO THE ENGLISH CHANNEL

As an example of the scheme, this chapter outlines the steps involved in applying the model and calculating the stratification parameter in the Southwestern Approaches. The area covered by the model is shown by the insert in Fig. 2; it extends from the Straits of Dover in the east and the north Channel of the Irish Sea in the north to the large open boundary south of Ireland in the southwest. The eastern and northern boundaries were placed at narrow sections to allow a better definition of the boundary conditions. Open boundaries, like the one to the southwest, should be avoided whenever possible because of the uncertainty involved in specifying the tidal constants in deep water. In the present circumstances, however, this choice of the boundary was unavoidable.

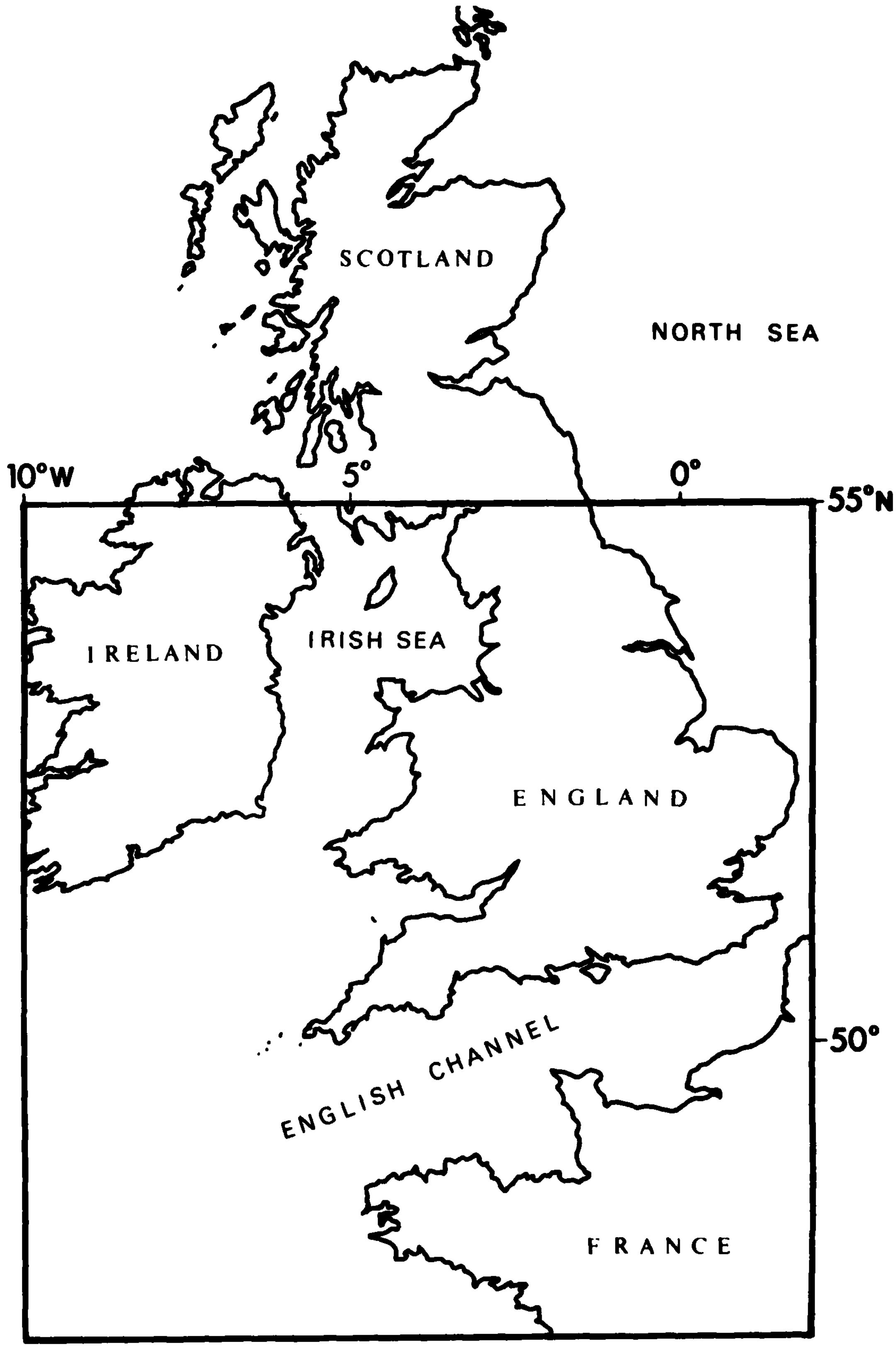


FIG. 2 THE COASTAL SEAS AROUND THE BRITISH ISLES, SHOWING THE AREA COVERED BY THE MODEL

The grid points of the model and the solid boundaries (i.e. the coastline) are shown in Fig. 3; a very crude grid has been used for the purposes of demonstration, to obtain more accurate results it would be necessary to use a much smaller grid spacing (see, for example, [7]). The corresponding water depths, defined at the elevation points, are shown in Fig. 4. The amplitudes and phases of the M_2 tide around the open boundary were taken from Flather [12] and are shown in Fig. 5 for the whole of the model region. (The boundary values are given in the subroutine BC). The major uncertainty (apart from the effect of the crude coastline representation) was the extrapolation of the tidal boundary conditions along the large open boundary. This was done by a process of trial and error until a reasonable agreement between the observed and computed tidal behaviour was obtained for the western entrance to the Channel. The computed phase and amplitude distributions are shown in Fig. 6. A fairly good agreement was achieved in the Approaches to the Channel and in the Channel itself, and also within the Bristol Channel. Note, however, that the agreement between the observed and computed distributions was poor throughout most of the Irish Sea.

The amplitudes shown in Figs. 5 and 6 are for the M_2 component alone. As part of the present study it was decided to investigate the variation of the stratification parameter (and hence the predicted frontal location) during the spring/neap cycle of the tide. The proper way to do this would be to specify the amplitude of both M_2 and S_2 around the open boundary, to run the model to simulate about one month of elapsed time, and to monitor the motion of the frontal location during the spring/neap cycle. A simpler way is to run the model for three cases:

a. Mean tidal conditions: amplitudes around the boundary given by M_2 alone.

b. Spring tides: amplitudes around the boundary given by $(M_2 + S_2)$.

c. Neap tides: amplitudes around the boundary given by $(M_2 - S_2)$.

Typical ratios of the $M_2{:}S_2$ amplitudes for the region were obtained from Heaps [13], and the open boundary amplitudes were scaled, to reproduce the three cases given above, in the ratios 1.0 : 1.4 : 0.6.

The results are shown in Figs. 7, 8 and 9, respectively. They suggest that the locations in which the front might possibly form cover a considerable proportion of the area at the western entrance to the Channel. However, as pointed out by James [6], the persistancy of a front during the spring/neap cycle is not well established. It is encouraging, however, that the calculated mean location of the front (Fig. 7) is in general agreement with the location determined from observations [5,7,13].

Some additional tests were made to determine the likely effect of storm-generated currents and their contribution to the stratification parameter. The strongest winds in this region are directed towards the east [14]; winds of Beaufort force 8 or greater occurring on average 35-40 days/year.

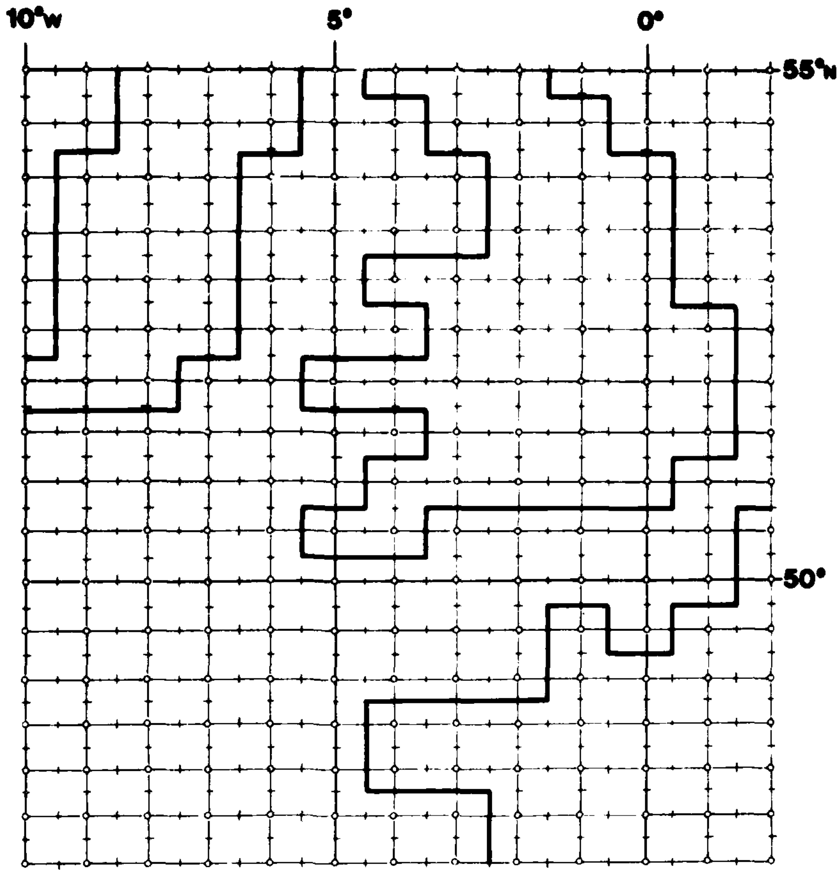
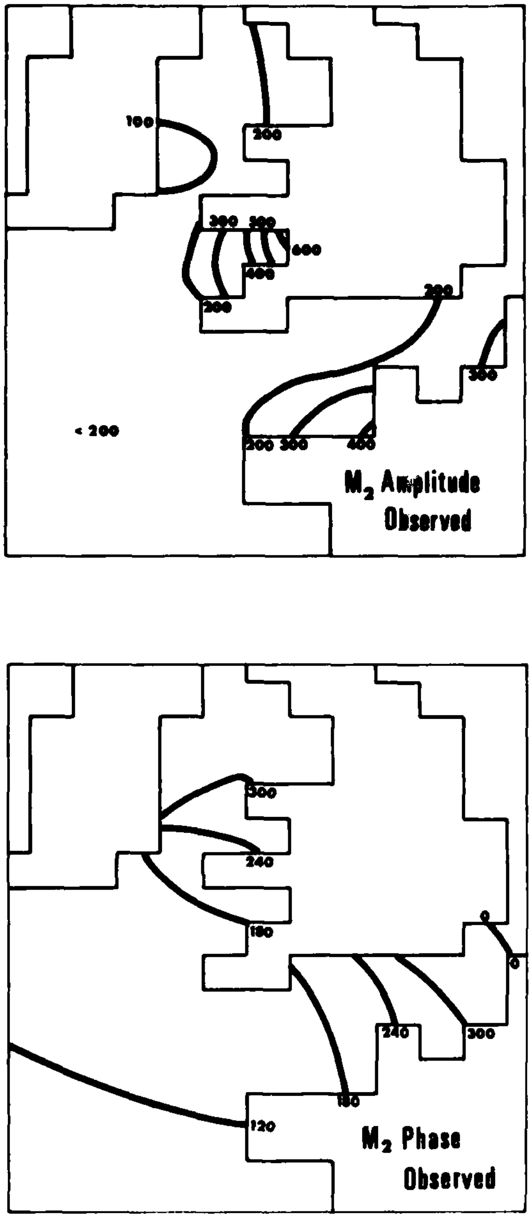


FIG. 3 DETAILS OF THE GRID LOCATION POINTS AND THE COASTLINE CONFIGURATION

.0	.0	.0	.0	64.0	36.0	.0	.0	.0	.0	.0
.0	.0	.0	9.0	54.0	36.0	7.0	.0	.0	.0	.0
.0	.0	.0	18.0	53.0	27.0	5.0	.0	.0	.0	.0
.0	.0	.0	7.0	73.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	36.0	73.0	7.0	.0	.0	.0	.0	.0
.0	.0	36.0	9.0	.0	.0	.0	.0	.0	.0	.0
18.0	73.0	82.0	100.0	45.0	18.0	.0	.0	.0	.0	.0
117.0	95.0	95.0	92.0	60.0	.0	.0	.0	.0	.0	9.0
91.0	73.0	110.0	82.0	.0	.0	36.0	18.0	27.0	45.0	11.0
104.0	110.0	110.0	44.0	55.0	73.0	66.0	82.0	62.0	36.0	7.0
146.0	120.0	128.0	110.0	92.0	84.0	55.0	18.0	.0	11.0	.0
160.0	120.0	146.0	120.0	106.0	88.0	18.0	9.0	.0	.0	.0
160.0	150.0	110.0	120.0	92.0	.0	.0	.0	.0	.0	.0
1830.0	360.0	126.0	106.0	92.0	.0	.0	.0	.0	.0	.0
3300.0	1850.0	360.0	137.0	130.0	92.0	11.0	.0	.0	.0	.0

FIG. 4 BOTTOM DEPTHS (metres) USED IN THE MODEL



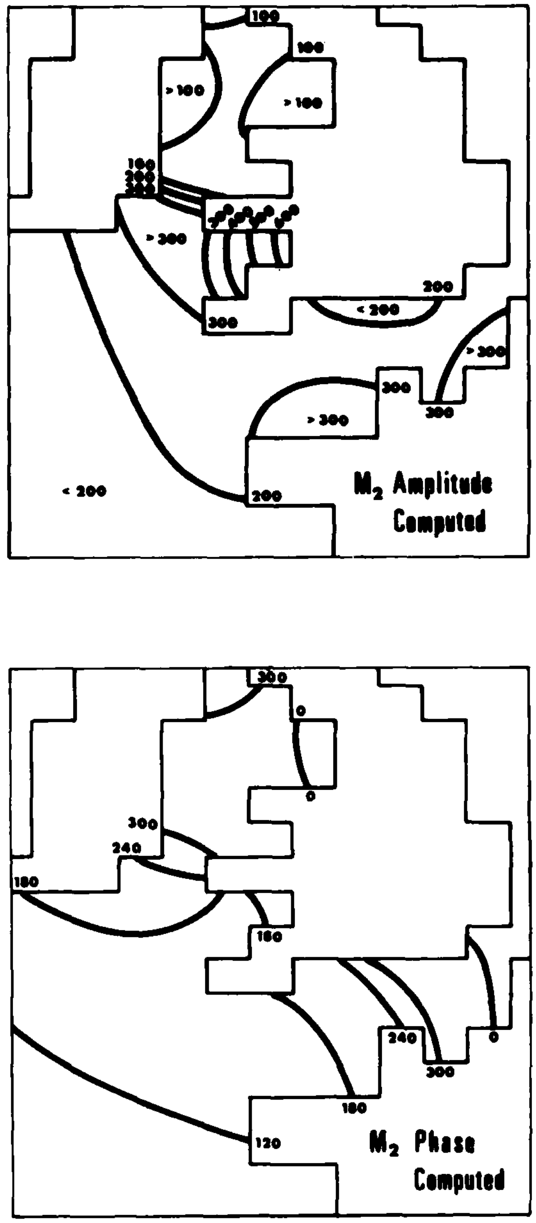


FIG. 5
THE OBSERVED AMPLITUDE AND PHASE OF THE M_2 TIDAL COMPONENT
(taken from [12])

FIG. 6
THE COMPUTED AMPLITUDE AND PHASE OF THE M_2 TIDE

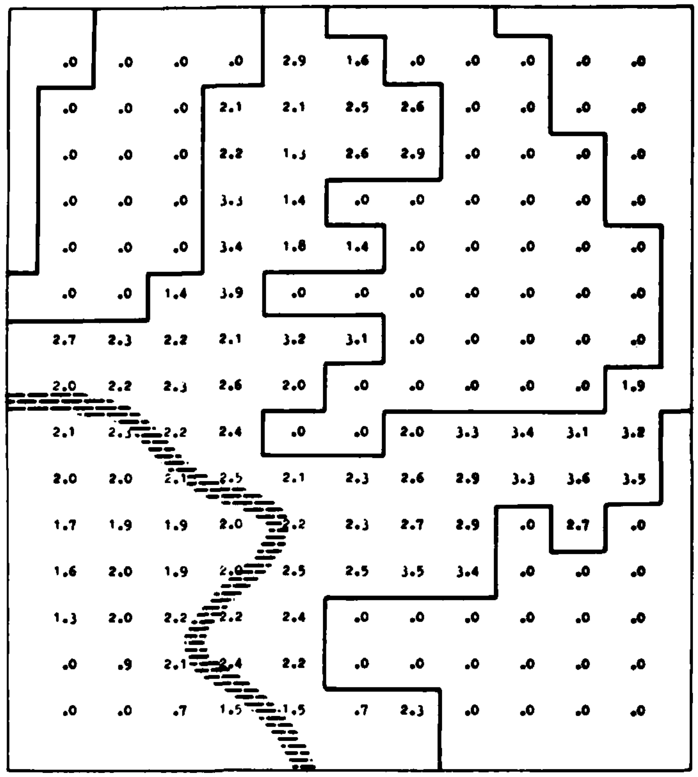


FIG. 7 CALCULATED VALUE OF THE STRATIFICATION PARAMETER $\log_{10}(u^3/h)$ FOR MEAN TIDAL CONDITIONS, THE CRITICAL VALUES ARE INDICATED

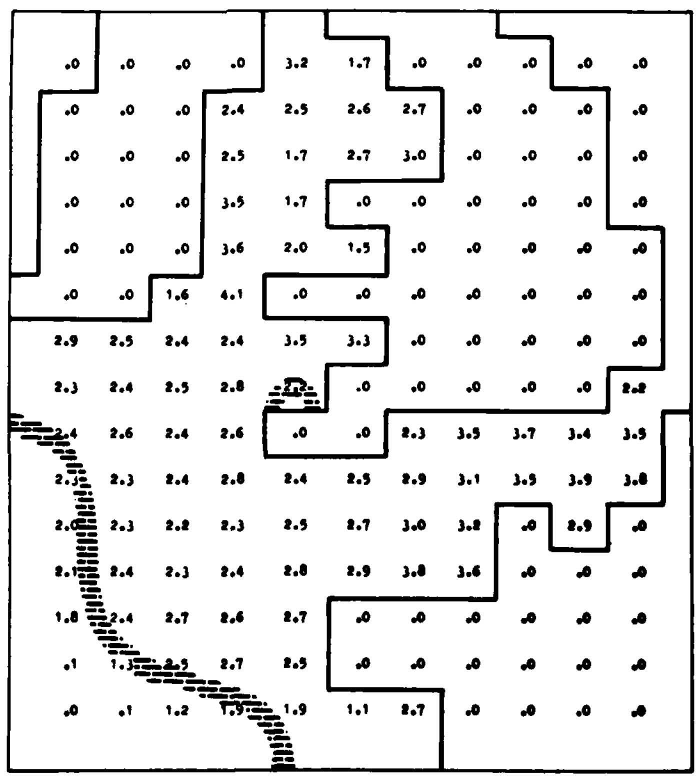


FIG. 8 CALCULATED STRATIFICATION PARAMETER FOR SPRING TIDES

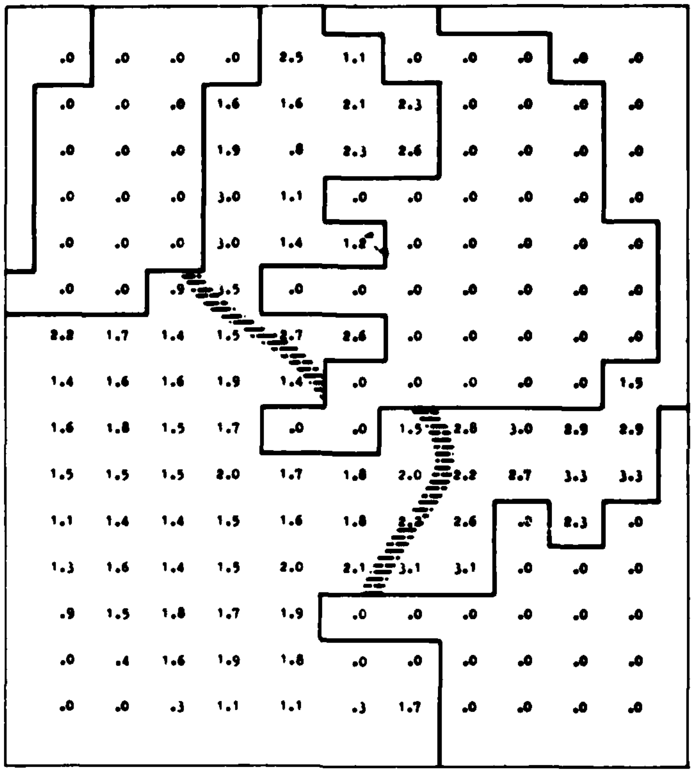


FIG. 9 CALCULATED STRATIFICATION PARAMETER FOR NEAP TIDES

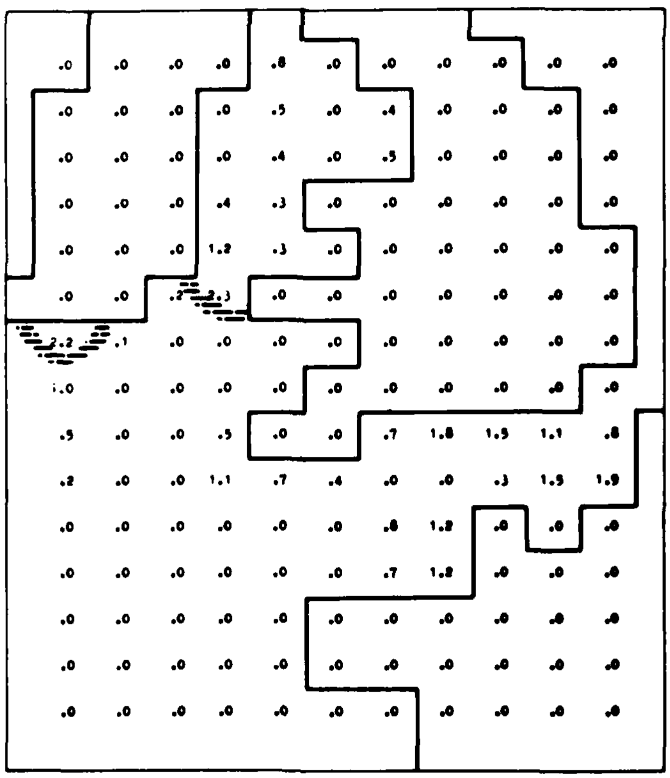


FIG. 10 CALCULATED STRATIFICATION PARAMETER DUE TO AN EASTWARD WIND OF 16 m/s

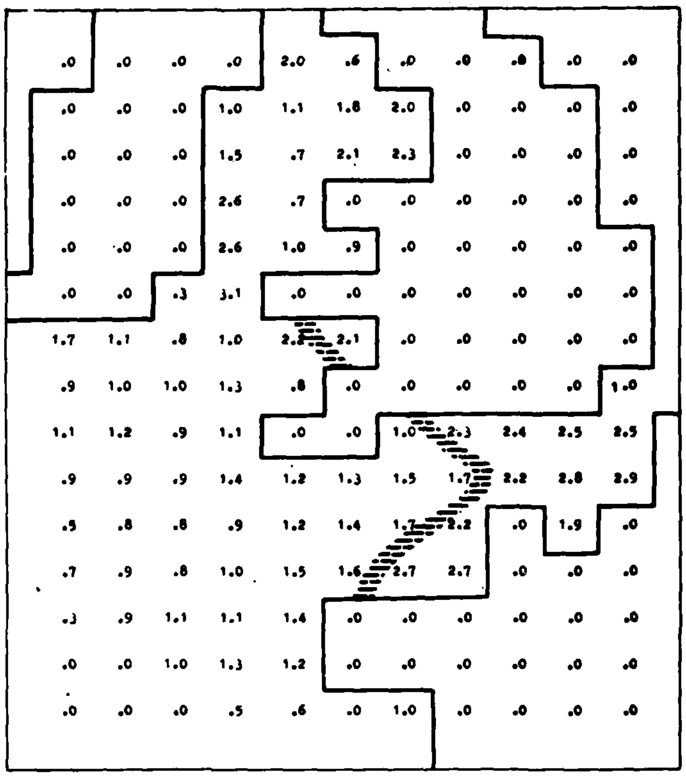


FIG. 11 CALCULATED STRATIFICATION PARAMETER FOR WEAK TIDAL CONDITIONS (boundary amplitudes equal to 0.3 mean tidal amplitudes)

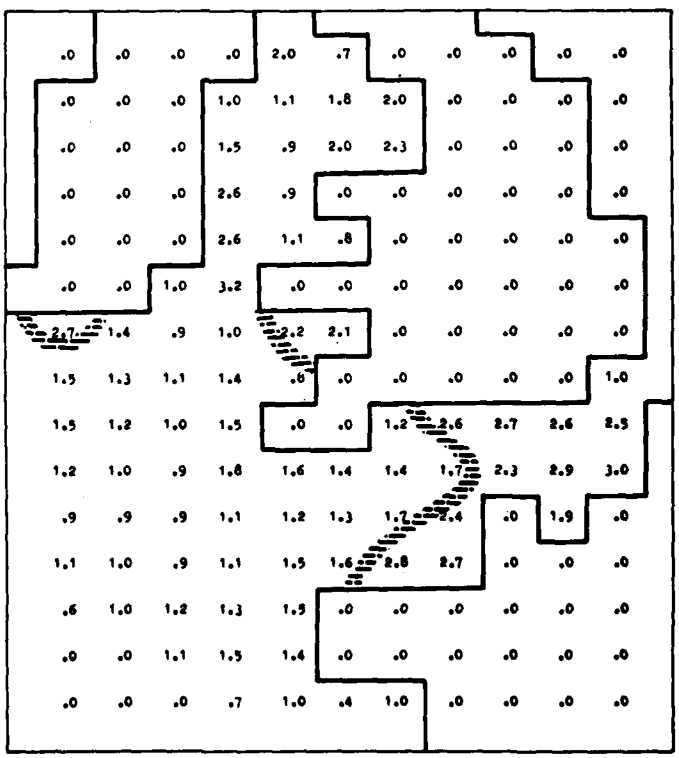


FIG. 12 CALCULATED STRATIFICATION PARAMETER FOR WEAK TIDES PLUS THE WIND USED IN FIG. 10.

This corresponds to an eastward wind of around 16 m/s, equivalent to a surface stress of 4 dyn/cm^2. To simulate the effect of such storms the model was run with a constant eastward wind stress and the wind-driven currents computed. As in the previous calculations the stratification parameter $\log_{10}(u^3/h)$ was estimated, based this time on the storm driven flow. (Note that this calculation ignores the downward vertical mixing due to the surface stirring of the wind; the model only takes account of the bottom-generated turbulence). The wind-driven flow was, almost everywhere, too weak to raise the stratification parameter to the critical value (Fig. 10). The only two exceptions were a location off the south coast of Ireland (where there was an easterly flow at about 1 kn (51 cm/s) in the shallow water) and in the Channel at the southern entrance to the Irish Sea (where the flow was southward at about 1 kn). Throughout the whole of the English Channel the wind-driven currents alone were too weak to cause the generation of a front. In general, the effect of wind driving was insignificant in comparison with the tidal effects, even weak tides being sufficient to mask the influence of the wind. To illustrate this point, Fig. 11 shows the effect of weak tides (boundary amplitudes set to 0.3 of the mean amplitudes), while Fig. 12 shows the effect of weak tides plus wind on the stratification parameter. It is clear from the figures that the tides dominate over the wind.

CONCLUSIONS

The purpose of this memorandum has been to present a readily adaptable scheme for predicting the likely locations at which thermal fronts might be formed by the bottom turbulence associated with the tides. The advantage of the method is that it requires only a knowledge of the behaviour of the tidal elevations around the open boundary, the internal dynamics within the region of interest are then computed numerically. By way of an example, the method was applied to an area that includes the Southwestern Approaches to the English Channel. To establish the computational grid, digitize the depth, and code the grid points and coastline required about five working days, the calculations described in the body of this memorandum required about 12 minutes of computer time each on a Univac 1106. Consequently, to apply the scheme to a new region and make all of the necessary computations would require about 10 man-days of effort (this figure should be maybe doubled or trebled if the individual is not familiar with the model).

In the present study the model was adjusted only for the area near the western entrance to the English Channel. Better results would probably be obtained if a higher resolution grid was used, and if more effort was spent on calibrating the predicted tide. In its application to the Southwestern Approaches the greatest uncertainty probably arises during the extrapolation of the tidal amplitude and phase along the open boundary to the southwest.

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APPENDIX A

THE PROGRAM LISTING

This appendix contains a listing of the FORTRAN program and subroutines required to make the calculations described in the main text. Comment cards have been inserted in the body of the program at the points where each input variable is introduced.

```
C
C      MAIN PROGRAM.
C
C      LOCATION OF TIDALLY GENERATED FRONTS.
C
C
C      WRITTEN BY:
C
C      A. J. ELLIOTT
C      SACLANTCEN, LA SPEZIA.
C      SEPTEMBER 1978.
C
C      THIS VERSION USES THE CALCOMP 960 PLOTTER.
C
C.....THE FOLLOWING COMMON BLOCKS SHOULD BE
C.....INSERTED AT THE BEGINNING OF EVERY SUBROUTINE.
C
       COMMON/C1/ U(20,30,3),V(20,30,3),S(20,30,3),C(20,30,3)
       COMMON/C2/ ETA(20,30,3),D(20,30),H(20,30,3),SIG(20,30),
      $SIGC(20,30)
       COMMON/C3/ UBAR(20,30),VBAR(20,30),SBAR(20,30),
      $CBAR(20,30),EBAR(20,30)
       COMMON/C4/ IU(20,30),IV(20,30),IE(20,30),IS(20,30)
       COMMON/C5/ K1(20,30),K2(20,30),N1,N2
       COMMON/C6/ G,DX,DY,DT,TOR,WX,WY,NX,NY,NX1,NY1,
      $NN,TC,TIM,NTC,F
       COMMON/C7/ IBUF(10),X(30),Y(30),Z(30,30),IPLOT1
      $,ZLEV(50),LABC(10),LWGT(10)
       COMMON/C8/ ROW(20,30,3)
       COMMON/C9/ NSUM
       COMMON/C10/ XA(20),YA(20),XB(20),YB(20),XC(20),YC(20),
      $XD(20),YD(20),XE(20),YE(20),XF(20),YF(20)
       REAL K1,K2,N1,N2
C
C.....
C
C
C
C      READ IN BASIC PARAMETERS.
C
C
C      DELTAX,DELTAY IN KM.
C
C      DELTAT IN SEC.
C
   100 FORMAT(F10.0)
       READ(5,100) DX
       READ(5,100) DY
       READ(5,100) DT
C
C      CONVERT TO CGS UNITS.
C
       DX=DX*10.**5.
       DY=DY*10.**5.
C
C      COMPUTATIONAL CONSTANTS.
```

```
C
C     BOTTOM FRICTION.
C
      TOR=2.5*10.**(-3.)
C
      G=981.
      OMEGA=7.272*10.**(-5.)
C
C     RRLAT IS THE LATITUDE.
C
      RRLAT=50.
      RLAT=RRLAT/180.*3.14159
      F=2.*OMEGA*SIN(RLAT)
C
      NTC=INT(12.4224*3600./DT+0.0001)
C
C     NX AND NY ARE THE DIMENSIONS OF THE WORKING GRID.
C
  101 FORMAT(I4)
C
      READ(5,101) NX
      READ(5,101) NY
C
      NX1=NX-1
      NY1=NY-1
C
C     NSTEP IS THE NO. OF ITERATIONS.
C
  102 FORMAT(I6)
      READ(5,102) NSTEP
C
C     NANS IS THE OUTPUT FREQUENCY.
C
      READ(5,101) NANS
C
C     READ IN THE ARRAYS WHICH DEFINE THE POINT TYPES.
C
      DO 200 I=1,NX1
  200 READ(5,103) ( IU(I,J),J=1,NY)
C
  103 FORMAT(50I1)
C
      DO 201 I=1,NX
  201 READ(5,103)  (IV(I,J),J=1,NY1)
C
      DO 202 I=1,NX
  202 READ(5,103)  (IS(I,J),J=1,NY)
C
      DO 203 I=1,NX
  203 READ(5,103)  (IE(I,J),J=1,NY)
C
C
C     SET ALL WORKING ARRAYS TO ZERO.
C
      DO 204 I=1,NX
      DO 204 J=1,NY
C
```

```
            DO 205 K=1,3
            U(I,J,K)=0.
            V(I,J,K)=0.
            S(I,J,K)=0.
            ETA(I,J,K)=0.
            C(I,J,K)=0.
            H(I,J,K)=0.
            ROW(I,J,K)=0.
  205       CONTINUE
C
            D(I,J)=0.
            SIG(I,J)=0.
            SIGC(I,J)=0.
            UBAR(I,J)=0.
            VBAR(I,J)=0.
            SBAR(I,J)=0.
            CBAR(I,J)=0.
            EBAR(I,J)=0.
            K1(I,J)=0.
            K2(I,J)=0.
  204       CONTINUE
C
            NN=0
            NSUM=0
C           READ IN THE DEPTHS AT S-POINTS (M.).
C
            DO 206 I=1,NX
  206       READ(5,104)  (D(I,J),J=1,NY)
  104       FORMAT(10F5.0)
C
C           READ IN THE FRESH WATER SOURCES (M**3/S).
C
            DO 208 I=1,NX
  208       READ(5,104)  (SIG(I,J),J=1,NY)
C
C
C           READ IN THE WIND SPEED AND DIRECTION (M/S AND DEGREES.
                                                   CURRENT CONVENTION)
            READ(5,100) WND
            READ(5,100) DIRN
C
C           COMPUTE THE COMPONENTS OF WIND STRESS.
C
            CC=1.3*10.**(-3.)
            ROWA=1.2*10.**(-3.)
            DIRN=(DIRN/180.)*3.14159
            WX=-CC*ROWA*10.**4.*WND*COS(DIRN)*WND
            WY=CC*ROWA*10.**4.*WND*SIN(DIRN)*WND
            DIRN=(DIRN*180.)/3.14159
C
C
C           READ IN THE HORIZONTAL EDDY STRESSES.
C
            READ(5,106) N1,N2
  106       FORMAT(2F10.0)
C
            READ(5,101) IPLOT1
C
```

```
C      IF IPLOT1 .EQ. 1 THE OUTPUT WILL BE PLOTTED.
C
       READ(5,105) START
 105   FORMAT(F5.0)
C
C
C      ESTABLISH THE INITIAL CONDITIONS.
C
       CALL INIT
C
C      OUTPUT THE INITIAL VALUES.
C
C
       WRITE(6,31)
 31    FORMAT(1H1)
 32    FORMAT(/)
       WRITE(6,110)
 110   FORMAT(5X,14HINITIAL VALUES///)
       WRITE(6,111) DX
 111   FORMAT(10X,10HDELTAX =   ,E10.3//)
       WRITE(6,112) DY
 112   FORMAT(10X,10HDELTAY =   ,E10.3//)
       WRITE(6,113) DT
 113   FORMAT(10X,10HDELTAT =   ,E10.3////)
       WRITE(6,114) TOR
 114   FORMAT(10X,25HBOTTOM FRICTION,  TOR =  ,E10.3//)
       WRITE(6,115) RRLAT
 115   FORMAT(10X,12HLATITUDE =  ,F5.0//)
       WRITE(6,116) WND,DIRN
 116   FORMAT(10X,14HWIND SPEED =  ,F5.0,10X,18HWIND DIRECTION =
       WRITE(6,117) N1,N2                                  ,F5.0/)
 117   FORMAT(10X,32HHORIZONTAL EDDY STRESSES  N1 =
      $E10.3//)              ,E10.3,10X,6HN2 =  ,
       WRITE(6,118) RK1,RK2
 118   FORMAT(10X,37HHORIZONTAL EDDY DIFFUSIVITIES  K1 =  ,
      $E10.3,10X,6HK2 =  ,E10.3//)
       WRITE(6,31)
C
C      OUTPUT THE WATER DEPTHS.
C
       WRITE(6,120)
 120   FORMAT(10X,21HWATER DEPTH IN METRES,//)
C
       DO 215 I=1,NX
       WRITE(6,32)
 215   WRITE(6,119) (D(I,J),J=1,NY)
 119   FORMAT(1X,16F7.1)
       WRITE(6,31)
C
       WRITE(6,121)
 121   FORMAT(10X,28HFRESH WATER SOURCES (M**3/S),//)
C
       DO 216 I=1,NX
       WRITE(6,32)
 216   WRITE(6,119) (SIG(I,J),J=1,NY)
C
C
```

```
C
C     CONVERT TO CGS UNITS.
C
      DO 207 I=1,NX
      DO 207 J=1,NY
      D(I,J)=D(I,J)*10.**2.
      H(I,J,1)=D(I,J)
      H(I,J,2)=D(I,J)
      SIG(I,J)=SIG(I,J)*10.**6.
  207 CONTINUE
C
C
C
C
C
C
      CALL OUTPUT
C
C
C     ***** START THE MAIN COMPUTATIONAL LOOPS ****
C     *****                                    ****
C     *****                                    ****
C     *****                                    ****
C     *****                                    ****
C     *****                                    ****
C
      TO=TOR
      TMAX=00.0
C
      DO 300 NN=1,NSTEP
C
      T=FLOAT(NN)*DT
      TIM=T/3600.
      TC=TIM/12.4224
C
C
      TOR=TO+TMAX/EXP(TC)
C
C
C
      CALL BC
C
      CALL ETA3
C
C
      CALL UVEL
C
      CALL VVEL
C
      CALL PARAM
C
C
C     ***** ALL VARIABLES HAVE NOW BEEN UPDATED****
C
C     UPDATE THE TIME INDEX.
C
      DO 720 I=1,NX
```

```
            DO 720 J=1,NY
            U(I,J,1)=U(I,J,2)
            U(I,J,2)=U(I,J,3)
            V(I,J,1)=V(I,J,2)
            V(I,J,2)=V(I,J,3)
            ETA(I,J,1)=ETA(I,J,2)
            ETA(I,J,2)=ETA(I,J,3)
            H(I,J,1)=H(I,J,2)
            H(I,J,2)=H(I,J,3)
  720       CONTINUE
C
C
C           TEST FOR OUTPUT.
C
            IF(TC .LE. START) GO TO 300
C
            IF(MOD(NN,NANS) .NE. 0) GO TO 699
C
C           PRINT OUT RESULTS.
C
            CALL OUTPUT
  699       CONTINUE
C
C
  300       CONTINUE
C
            IF(IPLOT1 .EQ. 0) GO TO 1255
            CALL PLOT(0.,0.,999)
  1255      CONTINUE
C
C
            STOP
            END
```

```
            SUBROUTINE INIT
C
C         SET THE INITIAL CONDITIONS.
C
C
C           INSERT THE INITIAL VALUES.
C
            DO 100 I=1,NX
            DO 100 J=1,NY
            DO 100 K=1,3
            IF(IS(I,J) .EQ. 1) GO TO 100
            ROW(I,J,K)=1.
  100       CONTINUE
C
            RETURN
            END
```

```
      SUBROUTINE OUTPUT
C
C     OUTPUT THE RESULTS.
C
C
      WRITE(6,31)
   31 FORMAT(1H1)
   32 FORMAT(/)
C
C     OUTPUT THE TIME IN HOURS.
C
      WRITE(6,25) TIM,TC
   25 FORMAT(10X,25HELAPSED TIME IN HOURS =   ,F6.2,50X,
     $26HNUMBER OF TIDAL CYCLES =   ,F6.2/)
C
C
      WRITE(6,100)
  100 FORMAT(5X,18HSURFACE ELEVATIONS/)
      DO 150 I=1,NX
      WRITE(6,32)
  150 WRITE(6,101) (ETA(I,J,2),J=1,NY)
  101 FORMAT(1X,16F7.1)
C
C
      WRITE(6,31)
      WRITE(6,102)
  102 FORMAT(10X,31HU-COMPONENT HORIZONTAL VELOCITY,///)
C
      DO 151 I=1,NX1
      WRITE(6,32)
  151 WRITE(6,101) (U(I,J,2),J=1,NY)
C
      WRITE(6,31)
      WRITE(6,103)
  103 FORMAT(10X,31HV-COMPONENT HORIZONTAL VELOCITY,///)
C
      DO 152 I=1,NX
      WRITE(6,32)
  152 WRITE(6,101) (V(I,J,2),J=1,NY1)
C
C
C+++
      WRITE(6,31)
      WRITE(6,104)
  104 FORMAT(10X,24HSTRATIFICATION PARAMETER,///)
C
      DO 153 I=1,NX
      WRITE(6,32)
  153 WRITE(6,101) (S(I,J,2),J=1,NY)
C
C     ++++++++++++++++++++++++++++++++++
C     ++++++++++++++++++++++++++++++++++
C
      IF(IPLOT1 .EQ. 0) GO TO 125
      CALL GRAPH
  125 CONTINUE
```

```
C
C     ***************************************
C     ***************************************
C
      RETURN
      END
```

```
      SUBROUTINE BC
C
C     SPECIFY THE TIDAL AMPLITUDES AND
C     PHASES AROUND THE OPEN BOUNDARY.
C
C
      SCALE=0.60
C
      ETA(1,6,3)=200.*SCALE*SIN(0.5058*TIM-0.0175*240.)
C
C
      DOV=SIN(0.5058*TIM)
C
C
      ETA(9,12,3)=250.*SCALE*DOV
      ETA(10,12,3)=300.*SCALE*DOV
      ETA(11,12,3)=350.*SCALE*DOV
C
C
      A=120.
      TT=0.5058*TIM
C
      ETA(8,1,3)=A*SCALE*SIN(TT-0.0175*150.)
      ETA(9,1,3)=A*SCALE*SIN(TT-0.0175*140.)
      ETA(10,1,3)=A*SCALE*SIN(TT-0.0175*130.)
      ETA(11,1,3)=A*SCALE*SIN(TT-0.0175*125.)
      ETA(12,1,3)=A*SCALE*SIN(TT-0.0175*120.)
      ETA(13,1,3)=A*SCALE*SIN(TT-0.0175*120.)
      ETA(14,1,3)=A*SCALE*SIN(TT-0.0175*115.)
      ETA(15,1,3)=A*SCALE*SIN(TT-0.0175*110.)
      ETA(16,1,3)=A*SCALE*SIN(TT-0.0175*105.)
      ETA(17,1,3)=A*SCALE*SIN(TT-0.0175*100.)
      ETA(17,2,3)=A*SCALE*SIN(TT-0.0175*100.)
      ETA(17,3,3)=A*SCALE*SIN(TT-0.0175*100.)
      ETA(17,4,3)=A*SCALE*SIN(TT-0.0175*100.)
      ETA(17,5,3)=A*SCALE*SIN(TT-0.0175*100.)
      ETA(17,6,3)=A*SCALE*SIN(TT-0.0175*100.)
      ETA(17,7,3)=A*SCALE*SIN(TT-0.0175*100.)
      ETA(17,8,3)=A*SCALE*SIN(TT-0.0175*100.)
C
      RETURN
      END
```

```
      SUBROUTINE ETA3
C
C     UPDATE THE SURFACE ELEVATIONS.
C
C
      DO 100 I=1,NX
      DO 100 J=1,NY
C
      IF(IE(I,J) .EQ. 1) GO TO 100
      IF(IE(I,J) .EQ. 2) GO TO 101
C
C     COMPUTATIONAL POINT.
C
      C1=SIG(I,J)/(4.*DX*DY*ROW(I,J,2))
      C2=-((H(I,J,2)+H(I+1,J,2))*U(I,J,2)-(H(I-1,J,2)+H(I,J,2))
     $ *U(I-1,J,2))/(4.*DX)
      C3=-((H(I,J,2)+H(I,J+1,2))*V(I,J,2)-(H(I,J-1,2)+H(I,J,2))
     $ *V(I,J-1,2))/(4.*DY)
C
C
C
      ETA(I,J,3)=ETA(I,J,1)+2.*DT*(C1+C2+C3)
C
  101 CONTINUE
      H(I,J,3)=ETA(I,J,3)+D(I,J)
C
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE UVEL
C
C     UPDATE THE U COMPONENTS.
C
      REAL MB1,MB2,MB3,MB4,MB5,MB6,MB7
      DO 100 I=1,NX1
      DO 100 J=1,NY
C
      IF(IU(I,J) .EQ. 1) GO TO 100
C
C     OUTSIDE THE GRID OR ON A BUY.
C
      MB3=WX
C
      MB6=-G*(H(I,J,2)+H(I+1,J,2))*(ETA(I+1,J,2)-ETA(I,J,2))/(4.*DX)
      MB7=-G*((H(I,J,2)+H(I+1,J,2))**2.)*(ROW(I+1,J,2)-ROW(I,J,2))
     $*(ROW(I,J,2)+ROW(I+1,J,2))**(-1.)/(8.*DX)
C
C     NEAR AN OPEN E-W BUY OR A CORNER.
C
      IF(IU(I,J) .EQ. 3 .OR. IU(I,J) .EQ. 4) GO TO 20
C
C     NORMAL EQUATION
      MB1=+N1*(H(I+1,J,1)*(U(I+1,J,1)-U(I,J,1))-H(I,J,1)*(U(I,J,1)
     $-U(I-1,J,1)))/(4.*DX**2.)
      GO TO 21
C
   20 MB1=0.
   21 CONTINUE
C
C
C     NEAR AN OPEN N-S BUY OR A CORNER.
C
      IF(IU(I,J) .EQ. 2 .OR. IU(I,J) .EQ. 4) GO TO 22
C
C     NORMAL POINT.
      HDSH1=0.25*(H(I,J,1)+H(I,J+1,1)+H(I+1,J+1,1)+H(I+1,J,1))
      HDSH2=0.25*(H(I,J-1,1)+H(I,J,1)+H(I+1,J,1)+H(I+1,J-1,1))
      MB2=+N2*(HDSH1*(U(I,J+1,1)-U(I,J,1))-HDSH2*(U(I,J,1)-U(I,J-1,1))
     $)/(4.*DY**2.)
C
      GO TO 23
C
   22 MB2=0.
   23 CONTINUE
C
C
C
C     NEAR AN OPEN N-S BUY OR A CORNER.
C
      IF(IU(I,J) .EQ. 2 .OR. IU(I,J) .EQ. 4) GO TO 24
C
      U1=U(I,J,1)
      U2=0.25*(V(I,J-1,1)+V(I,J,1)+V(I+1,J,1)+V(I+1,J-1,1))
      MB4=-0.5*(ROW(I,J,1)+ROW(I+1,J,1))*TOR*U1*SQRT(U1**2.+U2**2.)
      GO TO 25
```

```
      C
       24   MB4=-0.5*(ROW(I,J,1)+ROW(I+1,J,1))*TOR*
           $U(I,J,1)*ABS(U(I,J,1))
       25   CONTINUE
      C
      C
      C     NEAR AN OPEN N-S BDY OR A CORNER.
      C
            IF(IU(I,J) .EQ. 2 .OR. IU(I,J) .EQ. 4) GO TO 26
      C
            MB5=+F*(H(I,J,2)+H(I+1,J,2))*(V(I,J,2)+V(I+1,J,2)
           $+V(I+1,J-1,2)+V(I,J-1,2))/8.
      C
            GO TO 27
       26   MB5=0.
      C
       27   CONTINUE
      C
      C
            U(I,J,3)=(0.5*(H(I,J,1)+H(I+1,J,1))*U(I,J,1)
           $+2.*DT*(MB1+MB2+MB3+MB4+MB5+MB6+MB7))/(0.5*(H(I,J,3)
           $+H(I+1,J,3)))
      C
      C
      100   CONTINUE
            RETURN
            END
```

```
      SUBROUTINE VVEL
C
C     UPDATE THE V COMPONENTS.
C
      REAL MB1,MB2,MB3,MB4,MB5,MB6,MB7
      DO 100 I=1,NX
      DO 100 J=1,NY1
C
C     OUTSIDE THE GRID OR ON A BDY.
C
      IF(IV(I,J) .EQ. 1) GO TO 100
C
      MB3=WY
C
      MB6=-G*(H(I,J+1,2)+H(I,J,2))*(ETA(I,J+1,2)-ETA(I,J,2))/(4.*DY)
C
      MB7=-G*(H(I,J,2)+H(I,J+1,2))**2.*(ROW(I,J+1,2)-ROW(I,J,2))
     $/(ROW(I,J,2)+ROW(I,J+1,2))/(8.*DY)
C
C
C     NEAR AN OPEN E-W BDY OR A CORNER.
C
      IF(IV(I,J) .EQ. 3 .OR. IV(I,J) .EQ. 4) GO TO 20
      HDSH1=0.25*(H(I,J,1)+H(I,J+1,1)+H(I+1,J+1,1)+H(I+1,J,1))
      HDSH2=0.25*(H(I-1,J,1)+H(I-1,J+1,1)+H(I,J+1,1)+H(I,J,1))
      MB1=+N1*(HDSH1*(V(I+1,J,1)-V(I,J,1))-HDSH2*(V(I,J,1)-V(I-1,J,1)))
     $/(4.*DX**2.)
C
      GO TO 21
C
   20 MB1=0.
C
   21 CONTINUE
C
C     NEAR AN OPEN N-S BDY OR A CORNER.
C
      IF(IV(I,J) .EQ. 2 .OR. IV(I,J) .EQ. 4) GO TO 22
C
      MB2=+N2*(H(I,J+1,1)*(V(I,J+1,1)-V(I,J,1))-H(I,J,1)*
     $(V(I,J,1)-V(I,J-1,1)))/(4.*DY**2.)
C
      GO TO 23
C
   22 MB2=0.
C
   23 CONTINUE
C
C     NEAR AN OPEN E-W BDY OR A CORNER.
C
      IF(IV(I,J) .EQ. 3 .OR. IV(I,J) .EQ. 4) GO TO 24
C
      U1=0.25*(U(I-1,J,1)+U(I-1,J+1,1)+U(I,J+1,1)+U(I,J,1))
      U2=V(I,J,1)
C
      MB4=-0.5*(ROW(I,J,1)+ROW(I,J+1,1))*TOR*U2*SQRT(U1**2.+U2**2.)
      GO TO 25
```

```
C
   24 MB4=-0.5*(ROW(I,J,1)+ROW(I,J+1,1))*TOR*V(I,J,1)*ABS(V(I,J,1))
   25 CONTINUE
C
C
C     NEAR AN OPEN E-W BDY OR A CORNER.
C
      IF(IV(I,J) .EQ. 3 .OR. IV(I,J) .EQ. 4) GO TO 26
C
      MB5=-F*(H(I,J,2)+H(I,J+1,2))*(U(I-1,J,2)+U(I-1,J+1,2)
     $+U(I,J+1,2)+U(I,J,2))/8.
C
      GO TO 27
   26 MB5=0.
C
   27 CONTINUE
C
C
C
      V(I,J,3)=(V(I,J,1)*(H(I,J,1)+H(I,J+1,1))/2.+2.*DT*
     $(MB1+MB2+MB3+MB4+MB5+MB6+MB7))/((H(I,J,3)+H(I,J+1,3))/2.)
C
C
  100 CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE PARAM
C
C     COMPUTE THE STRATIFICATION PARAMETER.
C
C
      DO 100 I=2,NX1
      DO 100 J=2,NY1
C
      IF(IS(I,J) .EQ. 1) GO TO 100
C
      C(I,J,2)=(0.5*(U(I-1,J,2)+U(I,J,2))**2.
     $+0.5*(V(I,J-1,2)+V(I,J,2))**2.)
C
      C(I,J,2)=SQRT(C(I,J,2))
C
      STRAT=C(I,J,2)**3./D(I,J)+0.001
      C(I,J,2)=ALOG10(STRAT)
C
      IF(C(I,J,2).GT.S(I,J,2)) S(I,J,2)=C(I,J,2)
C
  100 CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE GRAPH
C
C     DO THE PLOTTING ON A CALCOMP*960.
C
C
C
C     DLEV          THE CONTOUR SPACING
C     HGTC          THE HEIGHT OF THE CONTOUR LABEL IN INCHES.
C     INDC          PERMITS CONTOUR LABELS TO VARY DURING A SINGLE PLOT.
C     LABC .GE. 0   NO. OF DIGITS IN CONTOUR LABEL DECIMAL PART.
C          = -1     NO DECIMAL PART.
C          = -3     NO LABEL PRINTED ON THE CONTOUR LINE.
C     LWGT=1        CONTOUR DRAWN BY ORDINARY LINE.
C         =2        HEAVY LINE.
C         =3        DASHED LINE.
C     NARC=1        VARIES 1-10 CAN BE USED TO SMOOTH THE CONTOURS.
C     NLEV          SUPPLIED BY GETLEV, IT IS THE NO. OF CONTOURS DRAWN.
C     NX,NY         WORKING DIMENSIONS OF THE ARRAY BEING CONTOURED.
C     X1PL,Y1PL     COORDINATES OF THE Z ORIGIN, I.E Z(1,1).
C     XLPL,YLPL     COORDINATES OF Z(NX,NY).
C     Z             ARRAY TO BE CONTOURED.
C     ZLEV          ARRAY SUPPLIED BY GETLEV.
C
C
C     THE FOLLOWING ARE THE PLOT OPTIONS.
C
C     IPLOT1=0      NO PLOT.
C     IPLOT1=1      PLOT ELEVATIONS AND VELOCITY VECTORS ONLY.
C     IPLOT1=2      ALSO PLOT SALINITY.
C
C
C
      DDX=0.7907
      DDY=0.9959
C
      FCX=2.*DDX*FLOAT(NX1)
      FCY=2.*DDY*FLOAT(NY1)
      XSHFT=2.*DDX*FLOAT(NX)+2.
      YSHFT=2.*DDY*FLOAT(NY)+2.
C
C     SET THE PLOTTING PARAMETERS.
C
      INDC=1
      LWGT=1
      HGTC=0.4
      LABC=-1
      NARC=1
C
C
C     IF NN=0 THEN CONTOUR THE BOTTOM TOPOGRAPHY.
C
      IF(NN.EQ. 0) GO TO 100
C
      GO TO 101
C
  100 CONTINUE
```

```
C
C     CONTOUR THE BOTTOM DEPTHS.
C
      CALL NEWPLT(4,'SWA',3,0)
      CALL FACTOR(0.5)
C
      DO 102 I=1,NX
      DO 102 J=1,NY
      Z(I,J)=D(I,J)/10.**2.
      IF(IS(I,J) .EQ. 1) Z(I,J)=10.**35.
  102 CONTINUE
C
C     SET CONTOUR SPACING AT 500 M.
      DLEV=500.
C
C
C
      CALL GETLEV(Z,NX,NY,DLEV,ZLEV,NLEV)
C
C     CONTOUR THE DEPTH.
C
      CALL PLOT(4.,7.,-3)
      CALL CONTUR(Z,NX,NY,0.,0.,FCX,FCY,ZLEV,LABC,LWGT,NLEV,HGTC,
     $NARC)
C
C     DRAW THE BOUNDARY.
C
      CALL BOUND
C
      CALL SYMBOL(0.,-2.,0.28,16HDX      DY      DT,0.,+16)
      CALL SYMBOL(5.0,-2.,0.28,23HTOR      WX      WY      F,
     $0.,+23)
C
      PDX=DX*10.**(-5.)
      PDY=DY*10.**(-5.)
C
      CALL NUMBER(0.,-3.,0.28,PDX,0.,+2)
      CALL NUMBER(2.,-3.,0.28,PDY,0.,+2)
      CALL NUMBER(4.,-3.,0.28,DT,0.,+2)
      CALL NUMBER(6.,-3.,0.28,TOR,0.,+4)
      CALL NUMBER(8.,-3.,0.28,WX,0.,+2)
      CALL NUMBER(10.,-3.,0.28,WY,0.,+2)
      CALL NUMBER(12.,-3.,0.28,F,0.,+6)
C
      CALL PLOT(0.,0.,999)
C
  101 CONTINUE
C
      IF(IPLOT1 .EQ. 1) CALL NEWPLT(4,'SWA',3,0)
      IF(IPLOT1 .EQ. 2 .OR. IPLOT1 .EQ. 3)
     $CALL NEWPLT(3,'SWA',3,0)
      CALL FACTOR(0.5)
C
      CALL PLOT(4.,7.,-3)
C
C     CONTOUR THE SURFACE ELEVATIONS.
C
```

```
      DO 110 I=1,NX
      DO 110 J=1,NY
      Z(I,J)=ETA(I,J,2)
      IF(IE(I,J) .EQ. 1) Z(I,J)=10.**35.
  110 CONTINUE
C
C     SET THE CONTOUR SPACING AT 100 CM.
C
      DLEV=100.
C
      CALL GETLEV(Z,NX,NY,DLEV,ZLEV,NLEV)
C
      CALL CONTUR(Z,NX,NY,0.,0.,FCX,FCY,ZLEV,LABC,LWGT,NLEV,HGTC,
     $NARC)
C
C
C     DRAW THE VELOCITY VECTORS.
C
      USCALE=0.02
C
      DO 120 I=1,NX1
      DO 120 J=1,NY1
C
      UMOD=U(I,J,2)**2.+U(I,J+1,2)**2.+ V(I,J,2)**2.+ V(I+1,J,2)**2.
C
      IF(UMOD .EQ. 0.) GO TO 120
C
C
      XCD=DDX+2.*FLOAT(I-1)*DDX
      YCD=DDY+2.*FLOAT(J-1)*DDY
C
      CALL SYMBOL(XCD,YCD,0.16,4,0.,-1)
C
      UBAR=0.5*(U(I,J,2)+U(I,J+1,2))
      VBAR=0.5*( V(I,J,2)+ V(I+1,J,2))
C
C
      XDSH=XCD+UBAR*USCALE
      YDSH=YCD+VBAR*USCALE
C
      CALL PLOT(XDSH,YDSH,2)
C
  120 CONTINUE
C
C
C     PLOT THE BOUNDARY.
C
      CALL BOUND
C
      CALL SYMBOL(1.,-2.,0.28,4HTC  ,0.,+4)
      CALL NUMBER(1.,-3.,0.28,TC,0.,+2)
      CALL SYMBOL(3.,-2.,0.28,5HTIM  ,0.,+5)
      CALL NUMBER(3.,-3.,0.28,TIM,0.,+2)
C
C     CONTOUR THE STRATIFICATION PARAMETER.
C
      IF((IPLOT1 .EQ. 2) .OR. (IPLOT1 .EQ. 3)) GO TO 130
```

```
      GO TO 131
  130 CONTINUE
C
      CALL PLOT(0.,YSHFT,-3)
C
      DO 132 I=1,NX
      DO 132 J=1,NY
      Z(I,J)=S(I,J,2)
  132 CONTINUE
C
C     SET CONTOUR SPACING AT 1
C
      DLEV=1.0
C
      CALL GETLEV(Z,NX,NY,DLEV,ZLEV,NLEV)
C
C
      CALL CONTUR(Z,NX,NY,0.,0.,FCX,FCY,ZLEV,LABC,LWGT,NLEV,HGTC,
     $NARC)
C
C
  131 CONTINUE
C
C     DRAW THE BOUNDARY.
C
      IF ((IPLOT1 .EQ. 2) .OR. (IPLOT1 .EQ. 3)) GO TO 150
      GO TO 151
  150 CONTINUE
C
      CALL BOUND
C
  151 CONTINUE
C
      CALL PLOT(0.,0.,999)
C
C
      RETURN
      END
```

```
      SUBROUTINE BOUND
C
C     DRAWS THE COASTAL BOUNDARY.
C
      COMMON /C10/ XA(20),YA(20),XB(20),YB(20),XC(20),YC(20),
     $XD(20),YD(20),XE(20),YE(20),XF(20),YF(20)
      DATA (XA(J),J=1,7)/0.,2.4,2.4,8.7,8.7,0.,1./
      DATA (YA(J),J=1,7)/3.,3.,1.,1.,0.,0.,1./
      DATA (XB(J),J=1,9)/0.,2.4,2.4,8.7,8.7,10.3,10.3,0.,1./
      DATA (YB(J),J=1,9)/9.,9.,7.,7.,5.,5.,0.,0.,1./
      DATA (XC(J),J=1,20)/0.,0.8,0.8,2.4,2.4,5.5,5.5,7.1,
     $7.1,8.7,8.7,10.3,10.3,11.9,11.9,13.4,13.4,15.0,0.,1./
      DATA (YC(J),J=1,20)/11.,11.,13.,13.,15.,15.,11.,11.,13.,13.,
     $9.,9.,13.,13.,11.,11.,9.,9.,0.,1./
      DATA (XD(J),J=1,15)/0.,0.8,0.8,2.4,2.4,7.1,7.1,11.9,11.9,
     $13.4,13.4,15.0,15.0,0.,1./
      DATA (YD(J),J=1,15)/17.,17.,19.,19.,21.,21.,
     $23.,23.,21.,21.,13.,13.,9.,0.,1./
      DATA (XE(J),J=1,15)/13.4,13.4,16.6,16.6,18.2,18.2,
     $16.6,16.6,19.8,19.8,22.9,22.9,25.3,0.,1./
      DATA (YE(J),J=1,15)/23.9,23.,23.,21.,21.,19.,
     $19.,17.,17.,11.,11.,15.,15.,0.,1./
C
C
C     DRAW THE BOUNDARY OF THE GRID.
C
      CALL PLOT(0.,0.,3)
      CALL PLOT(25.3,0.,2)
      CALL PLOT(25.30,23.9,2)
      CALL PLOT(0.,23.90,2)
      CALL PLOT(0.,0.,2)
C
C
      CALL LINE(XA,YA,5,1,0,0)
      CALL LINE(XB,YB,7,1,0,0)
      CALL LINE(XC,YC,18,1,0,0)
      CALL LINE(XD,YD,13,1,0,0)
      CALL LINE(XE,YE,13,1,0,0)
      RETURN
      END
```

1	27.78
2	33.34
3	74.5344
4	0017
5	0013
6	002200
7	0300
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21	25 55 55 11 11 11 1
22	25 55 55 11 11 11 1
23	43 33 33 33 11 11 1
24	11 11 11 11 11 11
25	11 11 15 11 11 11
26	11 11 55 51 11 11
27	11 11 55 51 11 11
28	11 11 51 11 11 11
29	11 11 55 11 11 11
30	11 15 11 11 11 11
31	25 55 55 11 11 11
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35	25 55 55 55 11 11
36	25 55 55 55 11 11
37	25 55 51 11 11 11
38	25 55 51 11 11 11
39	25 55 55 51 11 11
40	43 33 33 31 11 11
41	11 11 12 11 11 11 1
42	11 11 13 31 11 11 1
43	11 11 33 33 11 11 1
44	11 11 33 33 11 11 1
45	11 11 33 11 11 11 1
46	11 11 33 31 11 11 1
47	11 13 31 11 11 11 1
48	23 33 33 31 11 11 1
49	23 33 33 11 11 12 1
50	23 33 31 13 33 32 1
51	23 33 33 33 33 32 1
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83	.	.	.	.	7.	73.	.	.	.	.
84	.	.	.							
85	.	.	.	.	36.	73.	7.	.	.	.
86	.	.	.							
87	.	.	.	36.	9.	.	.	.	.	.
88	.	.	.							
89	36.	18.	73.	82.	100.	45.	18.	.	.	.
90	.	.	.							
91	137.	117.	95.	95.	92.	60.	.	.	.	.
92	.	9.	.							
93	146.	91.	73.	110.	82.	.	.	36.	18.	27.
94	45.	11.	.							
95	120.	104.	110.	110.	44.	55.	73.	66.	82.	62.
96	36.	7.	.							
97	128.	146.	120.	128.	110.	92.	84.	55.	18.	.
98	11.	.	.							
99	146.	160.	120.	146.	120.	106.	88.	18.	9.	.
100	.	.	.							
101	920.	160.	150.	110.	120.	92.	.	.	.	.
102	.	.	.							
103	2470.	1830.	360.	126.	106.	92.	.	.	.	.
104	.	.	.							
105	4350.	3300.	1850.	360.	137.	130.	92.	11.	.	.
106	.	.	.							
107	4400.	4200.	4400.	4600.	2600.	250.	150.	92.	.	.
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