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COMPUTER MODELING OF OIL DRIFT AND SPREADING IN DELAWARE BAY

by

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This research project was part of a program designed to delineate the effects on Delaware Bay of crude oil transfer and upstream refineries. Managed by the University of Delaware's College of Marine Studies, the 15-month program (1 March '74 - 31 May '75) was conducted under a $300,800 grant from the National Science Foundation's Research Applied to National Needs (RANN) Program, incorporating socio-economic assessments, engineering and oceanographic studies, as well as biological/ecological research. The research was conducted by the College of Marine Studies, the Departments of Civil Engineering, Biology and Geology, and the College of Business and Economics. Further information is available from the Program Manager, Dr. Robert Biggs, Assistant Dean, College of Marine Studies, University of Delaware, Newark, Delaware 19711, (302) 738-2842.

Already published under this program to date are: CMS-RANN-1-75: Sea Surface Drift Currents, by Jin Wu, CMS-RANN-2-75: Sport Fishing in Western Delaware Bay: Assessment of Critical Areas, by Ronal W. Smith, and CMS-RANN-3-75: Saturated Hydrocarbon Material in Sediments of the Delaware Estuary as Determined by Gas Chromatographic Analyses, by John F. Wehmiller and Margaret Lethen. Additional reports are in press, including baseline biological data on Delaware Bay.

ACKNOWLEDGMENTS

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LIST OF SYMBOLS

The following are symbols used in this paper:

A	= scalar turbulent eddy viscosity coefficient for upper layer of water
a_i	= autoregression coefficients
c	= concentration of oil at r from centroid
C	= tidal current magnitude
d	= local water depth
D	= maximum depth at which frictional and turbulent effects are important
E_r	= turbulent eddy viscosity coefficient for oil spreading on water
h	= thickness of oil spilled
$\vec{I}$	= unit vector in direction of deflected wind
k_c	= tidal drift coefficient
k_s	= wave drift correction coefficient
k_w	= wind drift coefficient
m	= total mass of oil spilled
p	= random number between 0 and 1
r	= radial coordinate
R_{gv}	= radius at which gravity-viscous spreading has ended
$R(t)$	= radius of oil from centroid
$\vec{R}(t)$	= vector oil slick displacement
Rx	= latitudinal component of oil drift
Ry	= longitudinal component of oil drift
t_{gv}	= time for which spreading has been cominated by gravity and viscous forces
$\vec{U}_c$	= vector tidal current magnitude
$\vec{U}_s$	= effective drift
$\vec{U}_w$	= vector random orodeterministic wind velocity
$\vec{U}_\eta$	= vector wave drift velocity
V	= total volume of oil spilled
w	= random or measured wind speed
$\vec{w}(t)$	= stochastically determined wind velocity vector
α	= deflection of wind direction caused by earth's rotation
Δt	= computational time step size at which all physical variables are refreshed by new ones

List of Symbols (Continued)

$\Delta\rho$ = density difference between oil and water

θ = random or measured wind direction (from north)

μ_w = absolute viscosity of water

ρ_o = density of oil

ρ_w = density of water

ϕ = local latitude

ψ = current direction (measured from north)

ω = earth's angular rotational rate

SUMMARY

The goal of the overall research program is to provide information for decision makers on oil transfer operations in Delaware Bay. The work reported here consists of only the computer model development. Other work, including data gathering of physical parameters and a detailed field verification program will be reported separately.

An interactive computer model for the prediction of oil spill dispersion was developed. Although the model is specifically developed for Delaware Bay application, the technique can easily be extended to other regions.

The model has two distinctive modes: drifting and spreading. The mechanism of drifting is based on the fact that oil on water drifts under the combined influence of water current, wind effects, and earth rotation. The physical processes governing the spreading of the slick are divided into three stages. In the initial stage, the spreading is predominantly governed by the balance of the forces of gravity and inertia. In the second stage, the spreading involves the balance of viscous and inertial forces. In the third and final stage of the spreading, a turbulent diffusion model is employed. Based on these processes and the approximation of radial symmetry, the rate of spreading can be computed.

The interactive nature of the model allows for information transfer between the computer and the users who may or may not be familiar with computer programming. The details of oil spill tracking are displayed on a Tektronix television-type screen. A number of output options are available. Examples are given together with field comparisons.

INTRODUCTION

Approximately 70 percent of all the oil that is delivered to the east coast of the United States moves by water up the Delaware Bay and River. Much of this oil is transferred several miles off the coast inside the Bay mouth from large deep-draft tankers to barges (lighters) or to small tankers to reduce the draft of the large tankers and allow navigation up the Bay and River for unloading at docks. More than 50 million short tons of crude petroleum was transported through the Bay using the Big Stone Beach Anchorage Area within the Bay (Figure 1).

Due, in part, to the nation's energy shortage, the oil transport through Delaware Bay and transfer activities in the Bay are expected to increase markedly in the future. National and regional concern over such development focuses in large measure on environmental vulnerability due to oil spills. Central to environmental repercussions, facility development, and clean-up operations is information regarding the physical movement and distribution of an oil spill.

A computer simulation model has been developed for tracing oil spills in the Delaware Bay. The model has two distinctive modes: drifting and spreading. The mechanism of drifting is based on the fact that oil on water drifts under the combined influence of water current, wind effect, and earth rotation. The physical processes governing the spreading of the slick are divided into three stages. In the initial stage, the spreading is predominantly governed by the balance of the forces of gravity and inertia. In the second stage, the spreading involves the balance of viscous and inertial forces. In the third and final stage of the spreading, a turbulent diffusion model is employed. Based on these processes and the approximation of radial symmetry, the rate of spreading can be computed.

The input requirements include the boundary conditions (the geometry and bottom topography), the tidal current, the wind condition, and the nature of the oil spill – viz., the size of the spill, location of the initial spill and the nature of the oil. Contemporary tidal current information and wind conditions in the Delaware Bay region are now being used as input.

The wind condition can be entered in either of two ways. It can be entered at finite time increments with known and predetermined values or with computed outcome for stochastic analysis of past wind records. The former way provides an oil tracking routine, and the latter input yields information on the probability of oil spill distributions.

The interactive nature of the model allows for information transfer between the computer and the users who may or may not be familiar with computer programming. The details of oil spill tracking are displayed on a Tektronix television-type screen. A number of output options are available.

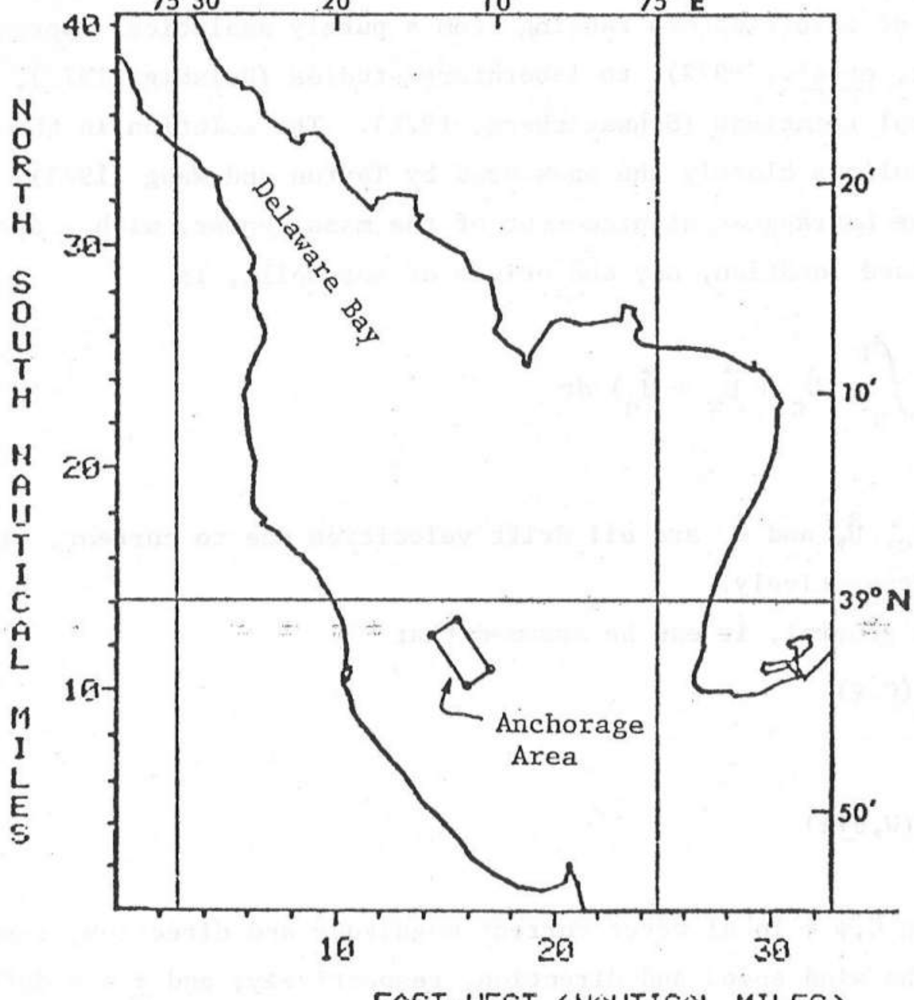


Figure 1 Delaware Bay Oil Tanker Anchorage Area

PROBLEM FORMULATION

Mechanics of Drifting

In considering oil drift, one should consider the effects of overwater winds, waves, and current. This problem has been studied by a number of investigators ranging from a purely analytical approach (Warner, et al., 1972), to laboratory studies (Reisbig, 1973), to empirical relations (Schwartzberg, 1971). The solution in the present model follows closely the ones used by Tayfun and Wang (1973).

The Lagrangian displacement of the mass center, with respect to a fixed location, say the origin of the spill, is

$$\vec{R}(t) = \int_0^t (\vec{U}_c + \vec{U}_w + \vec{U}_\eta)\, dt \qquad (1)$$

where $\vec{U}_c$, $\vec{U}_w$ and $\vec{U}_\eta$ are oil drift velocities due to current, wind, and waves respectively.

In general, it can be assumed that

$$\vec{U}_c = \vec{U}_c(C, \Psi) \qquad (2)$$

$$\vec{U}_w = \vec{U}_w(W, \theta \pm \alpha) \qquad (3)$$

in which C, ψ = local water current magnitude and direction, respectively; w, θ = the wind speed and direction, respectively; and $\pm\,\alpha$ = deflection of the wind drift with respect to the wind direction in the southern and northern hemispheres, respectively, with θ being measured as positive counterclockwise.

Since oil drift is evidently a result of momentum transfer, and the intensity of the momentum is proportional to the velocity, it is natural to assume that a linear relationship exists between the drift velocity and the velocity of the wind and water, i.e.,

$$\vec{U}_c = k_c \vec{C} \qquad (4)$$

$$\vec{U}_w = k_w W \vec{i}\ (\theta \pm \alpha) \tag{5}$$

where i is a unit vector which deviates from wind direction by an angle, α, due to earth rotation.

Apparently the coefficients, k_c and k_w, are functions of oil characteristics, sea conditions and, perhaps, temperature. For calm water, it is generally agreed that the value of k_w is around 0.03. Schwartzberg suggested that the value of k_c should be around 0.56.

The exact effect of waves on oil drift is not known. However, one may reason that waves play a role in that they increase the surface roughness of the sea at least, and produce a surface drift themselves. While the surface roughness definitely affects the wind drift, the wind drift contributes directly to the water drift. The laboratory work by Reisbig seemed to suggest that at low wind speeds wave drift augments the wind drift. However, at higher wind speeds, the waves cause a net decrease in drift velocity. For lack of better understanding of the exact effect due to waves, a correction coefficient, k_s, is incorporated into the present model, so that

$$\vec{U}_s = k_s k_w W \vec{i}\ (\theta \pm \alpha) \tag{6}$$

The wave correction coefficient, k_s is evidently a function of wave steepness and wind velocity, as is shown in Figure 2. The deflection angle, α, is computed according to the following formula (Neumann, 1968), under the assumption of steady state and shallow water conditions:

$$\tan \alpha = \frac{\sinh (2\pi \frac{d}{D}) - \sin (2\pi \frac{d}{D})}{\sinh (2\pi \frac{d}{D}) + \sin (2\pi \frac{d}{D})} \tag{7}$$

in which d = the local water depth and D = depth of frictional influence, given by

$$D = \pi \left(\frac{A}{\rho\ \omega \sin \phi}\right)^{1/2} \tag{8}$$

where A is the eddy viscosity coefficient in the upper strata of the oceans; ρ = the density of water; and ϕ = the local latitude. Based on the values $\rho = 1\ g/cm^3$; $\omega = 7.29 \times 10^{-5}$ rad/sec and $A \approx 100$ g/cm-sec, the value D is approximately 46 m (150 ft).

Equations (4), (6), (7) and (11) constitute the basic formulation of

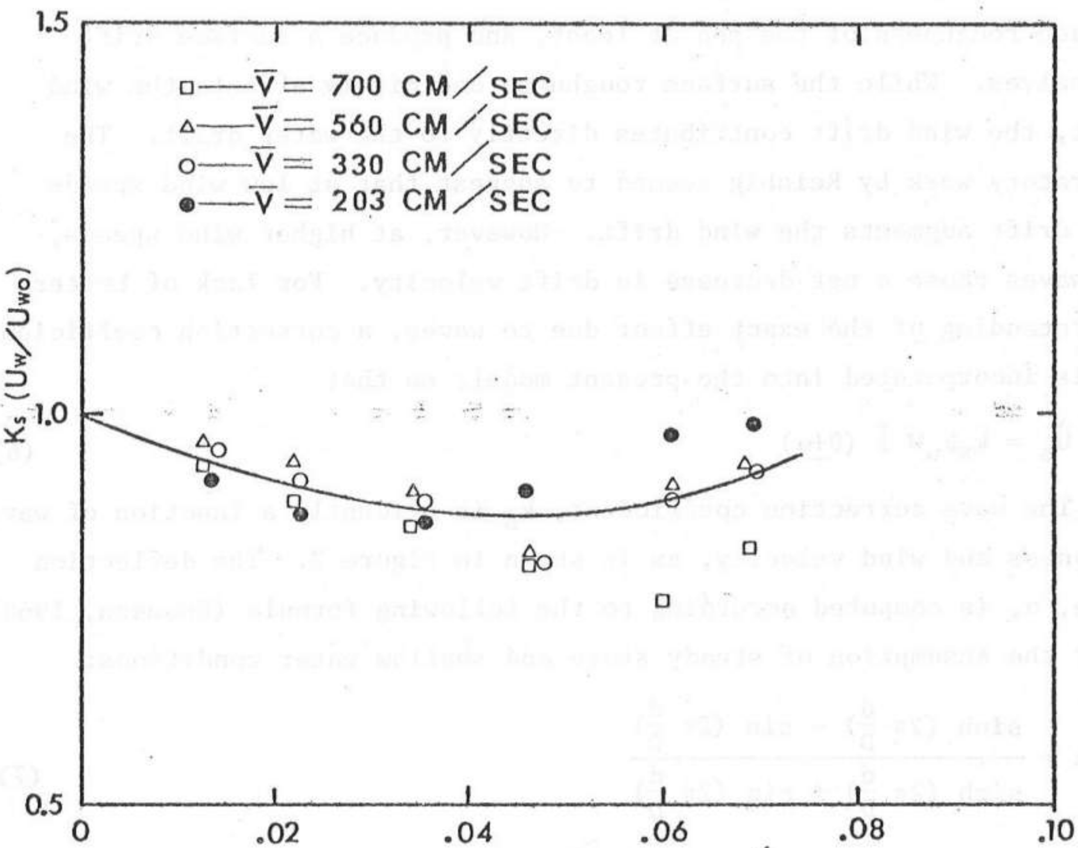


Figure 2 Drift Speed Correction Coefficient as a Function of Wave Steepness (Data from Reigsbig, 1973)

oil drift.

Mechanics of Spreading

The problem of physical processes in the spreading of oil on a water surface has been studied by several investigators; Fay (1971), Schwartzberg (1971), Ichiye (1972), Warner, et al. (1972 and Murray, et al. (1970) are but a few of them.

Approaching the problem from the point of view of the basic mechanics of oil spreading, Fay suggested that the spilling of oil passes through three stages as time progresses: 1) the gravity-inertia stage where the gravity force is counterbalanced by the inertia force; 2) the gravity-viscous stage where the inertia force of the oil mass becomes insignificant and the gravity force is basically resisted by the viscous force; and the final stage, 3) the surface tension-viscous force stage when surface tension becomes the driving force and is counteracted by the viscous force. Laboratory results revealed that the surface tension-viscous stage dominates the other two. However, field experience seemed to indicate that, except for a short period (within a few hours), the spreading and decay of the oil slick can be treated as a diffusion process (Ichiye, 1972; Murray, et al., 1970). Thus, although in the laboratory the surface tension-viscous stage is an important one, such a mechanism does not seem to be effective in the field.

Based on the above argument, the spreading model used here consists of three stages, namely the gravity-inertial, the gravity-viscous, and the diffusion stages. The equations for the respective earlier stages are as follows: (Fay, 1971)

Gravity-Inertial Stage

$$R(t) = 1.14\ (V)^{1/3}\ [\frac{g\Delta\rho}{\rho_w V^{1/3}}]^{1/4}\ t^{1/2} \qquad (9)$$

Gravity-Viscous Stage

$$R(t) = 0.98\ (V)^{1/3}\ (\frac{g\rho_o\Delta\rho}{\rho_w})^{1/6}\ (\rho_w\mu_w)^{-1/12}\ t^{1/4} \qquad (10)$$

where R is the radius of spill size; V is the volume of spill; g is the gravitational acceleration, ρ_o is the density of oil, ρ_w is the density of water, $\Delta\rho$ is the density difference between water and oil, μ_w is the viscosity of water and t is the time.

The oil spreading at the diffusion stage is based on the assumption that at a certain period after the spills, the oil can be treated as a diffusible material. Thus, the diffusion equation is applicable.

$$\frac{\partial c}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\, E_r\, \frac{\partial c}{\partial r}\right) \tag{11}$$

where c is the concentration; r is the radius of spreading, E_r is the turbulent diffusion coefficient. The value of E_r for oil in ocean waters is not quite known. Ichiye (1972) stated that E_r should be a function of the spill size, wind velocity, and wind direction. Murray (1970), on the other hand, treated E_r as a constant in his study and claimed good comparison with field results. For the case where E_r is equal to the constant, the solution of Equation (11) becomes

$$c = \frac{m}{4\pi\, \rho_o h E_r t}\, e^{(-r^2/4E_r t)} \tag{12}$$

where m is the total mass of the oil spill; h is the thickness of the oil spill. Equation (12) indicates that

$$R \propto t^{1/2} \tag{13}$$

When Equations (12) and (13) are used to match with the two previous stages, this results in

$$R = 2\sqrt{2\, E_r(t - t_{gv}) + (R_{gv/2})^2} \tag{14}$$

where the subscript gv indicates the conditions at the end of the gravity-viscous stage.

Equations (9), (10), and (14) are then matched to provide the complete solution for oil spreading. The criteria of matching are based upon the size of the spill as suggested by Waldman et al. (1973). Figure 3 delineates these criteria.

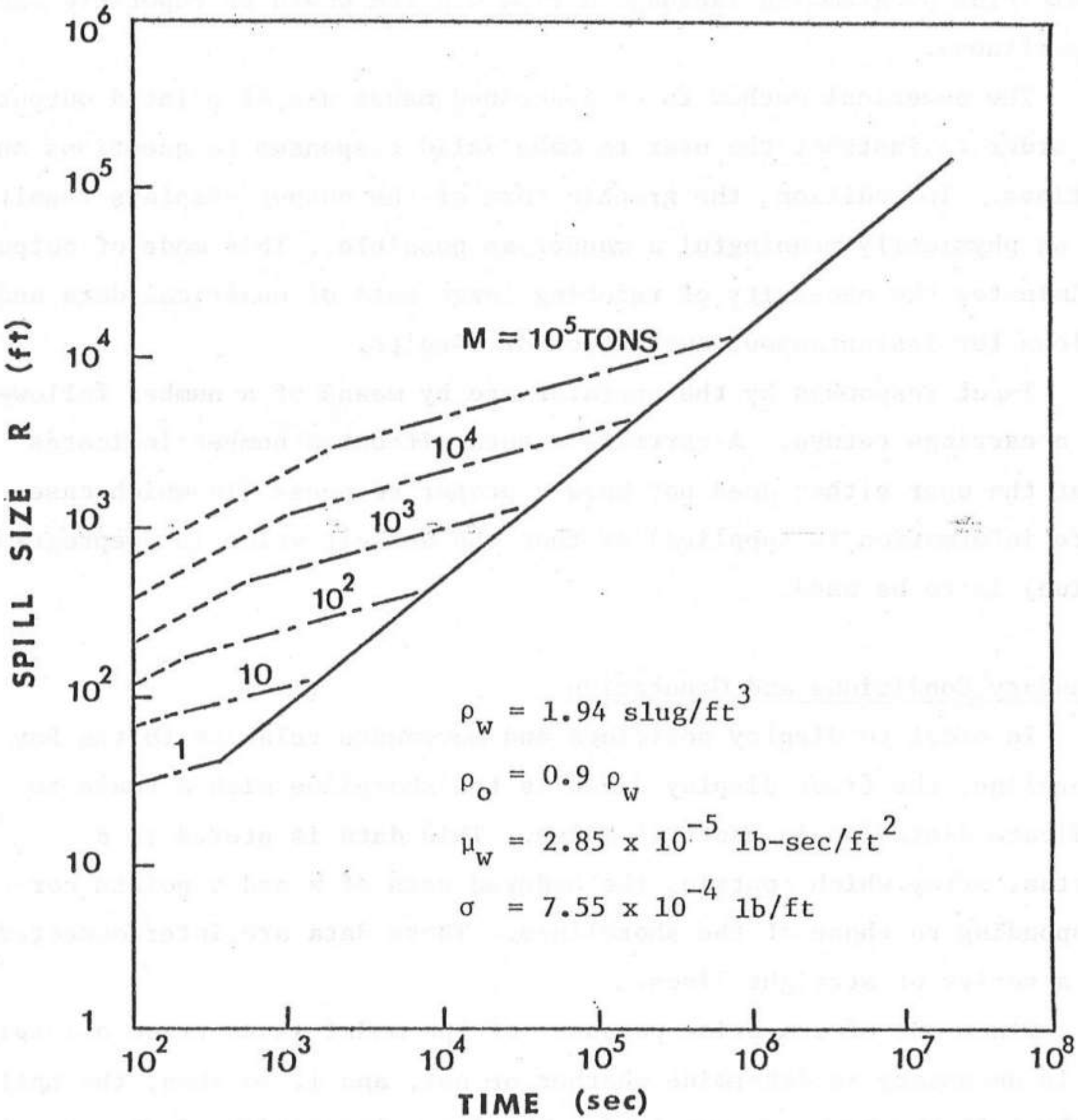


Figure 3 Match Criteria for Different Oil Spilling Mechanism
(From Waldman, et al., 1973)

COMPUTER SIMULATION TECHNIQUE

The method of simulation used in this study is virtually language independent and is viable for any general-purpose programming language. An earlier version of the program was written in Fortran and has been converted into Basic-Plus for use on the P.D.P. system 11 minicomputer. Because of the structural nature of the program made possible by the Basic-Plus programming language a flow diagram would be repetitive and superfluous.

The numerical method to be described makes use of printed output in order to instruct the user to make valid responses to questions and options. In addition, the graphic form of the output displays results in as physically meaningful a manner as possible. This mode of output eliminates the necessity of reducing large sets of numerical data and allows for instantaneous evaluation of results.

Input responses by the operator are by means of a number followed by a carriage return. A carriage return without a number indicates that the user either does not know a proper response (in which case more information is supplied) or that the default value (a preprogrammed value) is to be used.

Boundary Conditions and Generation

In order to display positions and movements relative to the Bay shoreline, the first display drawn is the shoreline with a scale to indicate distances in nautical miles. This data is stored in a virtual array which contains the ordered sets of x and y points corresponding to those of the shorelines. These data are interconnected by a series of straight lines.

Since one of the prime purposes of the model is to trace oil spills, it is necessary to determine whether or not, and if so when, the spill drifts off the Bay and onto land. The irregular nature of the shorelines make these logical decisions very difficult. A complete search of the shoreline data is extremely inefficient. In order to avoid this, a method is devised which expedites decisions on boundary locations. A one-dimensional integer array is created to store the number of times a horizontal line through a row of grid points crosses the shoreline boundaries. A two-dimensional integer array then stores the beginning and ending number of grid points which lie in the bay for a particular row. This method provides an advantage over a complete search through the data in that only the beginning and ending number of gridpoints must be stored in order to determine the extremities. This greatly lowers the amount of information to be checked in deciding on interior and exterior points to the bay. It also hastens the logical process since only integers are involved.

Simulation of Environmental Conditions

One of the more difficult and controversial aspects of numerically modelling the transport process in oceanic environment is the predictive methods to be employed for the generation of water movement information. The governing equations of the hydrodynamic processes are nonlinear, both in the equations themselves and in the boundary conditions. Analytical solutions are, in general, unobtainable. Although a number of numerical schemes are available, their application is tedious, requiring lengthy calibration and sometimes extensive modification. For a boundary condition as complicated as Delaware Bay, the adoption of a hydrodynamic model for current prediction appears impractical.

By using field measurements of the tidal currents and winds these difficulties may be avoided for the most part. Although this process requires efficient means of storing and utilizing large amounts of data, the process may be optimized to the point where the simulation will run in much less than real time and with memory restrictions imposed by a minicomputer. The bay currents C used by the model are those measured by the U.S. Coastal and Geodetic Survey (1960). They are stored in a virtual array similar to the one used for the shoreline points. However, whereas the order is important for the shoreline points so that they are connected simultaneously, the order is not important for the tidal currents. The virtual array is, however, divided into six segments in order to separate the various tidal phases of a full tidal cycle. These six segments are thus recycled as necessary in order to continually recycle the tidal currents.

The six segments contain four numbers for each data point. The first two numbers are respectively the x and y locations at which the measurements were taken. The third and fourth numbers are the magnitude and direction of the currents. By means of this type of file structuring, the tidal phase for the beginning of the simulation may also be chosen by the user.

In order to select a particular current for a point in the bay the closest point with measured current data is chosen. The complete segment for that tidal phase is tested in order to find the closest value. A more sophisticated interpolation procedure seemed unnecessary in view of the crude nature of the data.

The wind may be accounted for in the model in either of two ways. The operator may choose to enter wind speeds and direction on the basis of two-hour intervals for the duration of the physical time to be simulated. This allows for data based on forecasting or recent field measurements to be used in a deterministic manner.

An alternative to the deterministic mode of operation is probabilistic determination of the wind. The wind speed and direction are modelled by means of a linearly correlated time series and a uniformly distributed random number with the same variance as though calculated by measurements. The model for the velocity is as follows:

$$|\vec{w}(t)| = a_1|\vec{w}(t-\Delta t)| + a_2|\vec{w}(t-2\Delta t)| + a_3|\vec{w}(t-3\Delta t)| + a_4|\vec{w}(t-4\Delta t)| + P \quad (15)$$

where a_1, a_2, a_3, and a_4 are the autoregression coefficients and P is a random number with a variance determined by the standard deviation of the autoregression analysis. The solution for the coefficients of the terms and the random number has been presented by Tayfun and Wang (1973). For the present model, wind data at Dover Air Force Base, Delaware (approximately 14 miles northwest of the anchorage area) are used.

Drifting and Spreading

Equation (1) is used for the computation of the drifting of the center of the mass. All effects are assumed fairly uniform over a finite size time step so that the equations for the prediction of the x and y coordinates of the center of the spill are respectively

$$R_x(t+\Delta t) = R_x(t) + (\vec{U}_c + \vec{U}_w + \vec{U}_\eta)_x \, \Delta t \quad (16)$$

$$R_y(t+\Delta t) = R_y(t) + (\vec{U}_c + \vec{U}_w + \vec{U}_\eta)_y \; \Delta t \tag{17}$$

An example of the deterministic method is shown in Figure 4. For this case a steady wind of 20 knots is assumed to blow from the southeast for a period of 40 hours. The initial spill is assumed to be 500 tons, occurring during a period tide at the location of 38° 56' Lat. and 75° 06' Long.

While in the deterministic mode, Equations (16) and (17) are applied only once for each time step increment, the same computational procedures will have to be repeated a large number of times to be statistically meaningful if the probabilistic mode of the program is used. Recalling that the main purpose of the probabilistic mode is to provide estimations of probable spill routines during a designated period of the year, the larger the repeated trials the more reliable the results. An example of this type of simulation in order of time sequence up to 40 hours is shown in Figure 5, with 200 individual experiments. If the number of particles are counted within each grid, an approximate conditional probability that an oil slick will appear in that grid can be created in the form of a percentage. Such a display is shown in Figure 6. The effect of the number of experiments is clearly demonstrated in this figure.

The rate of spreading about the center of the mass is determined by Equations (9), (10) and (14) for the various regimes. The spreading begins with the Gravity-Inertial Stage [Equation (9)]. The time for which the Gravity-Viscous Stage becomes important may be calculated by setting the radius predicted by Equation (9) equal to the radius predicted by Equation (10) and solving for the time t. The time at which to begin use of Equation (14) is solved for in a similar manner. The sizes of the slick at successive time increments are printed on the display and, at the user's option, can be drawn on the graph. Output of this type is shown in Figure 5. A number of other auxiliary output options such as bay current and an oil drift speed diagram are also available in Figure 7.

Data Retrieval and Usage

The numberical model described above obviates the need for special handling of vast amounts of data, thus making the method quite attractive

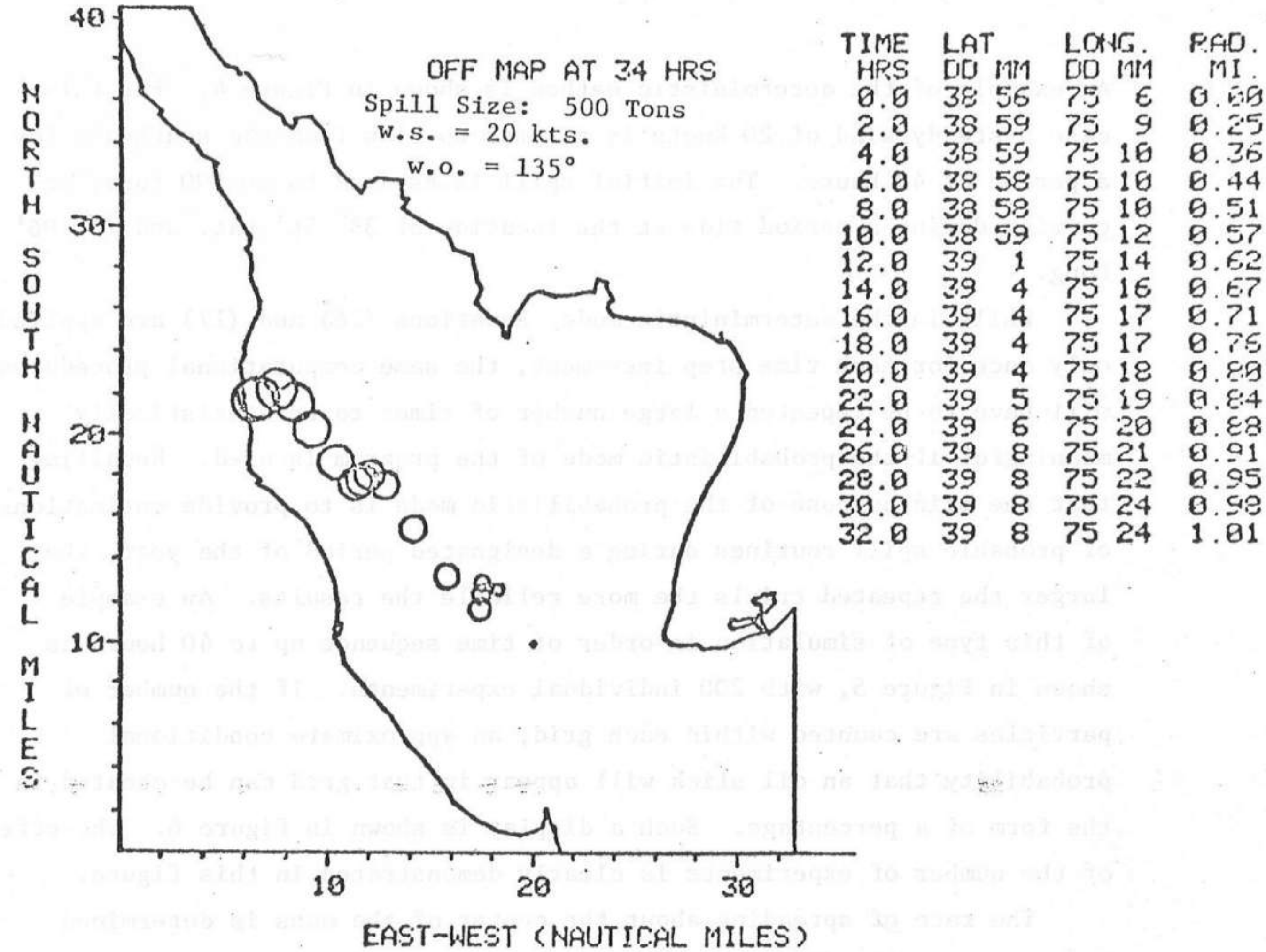


Figure 4 Example of Oil Slick Drifting and Spreading (Deterministic Mode)

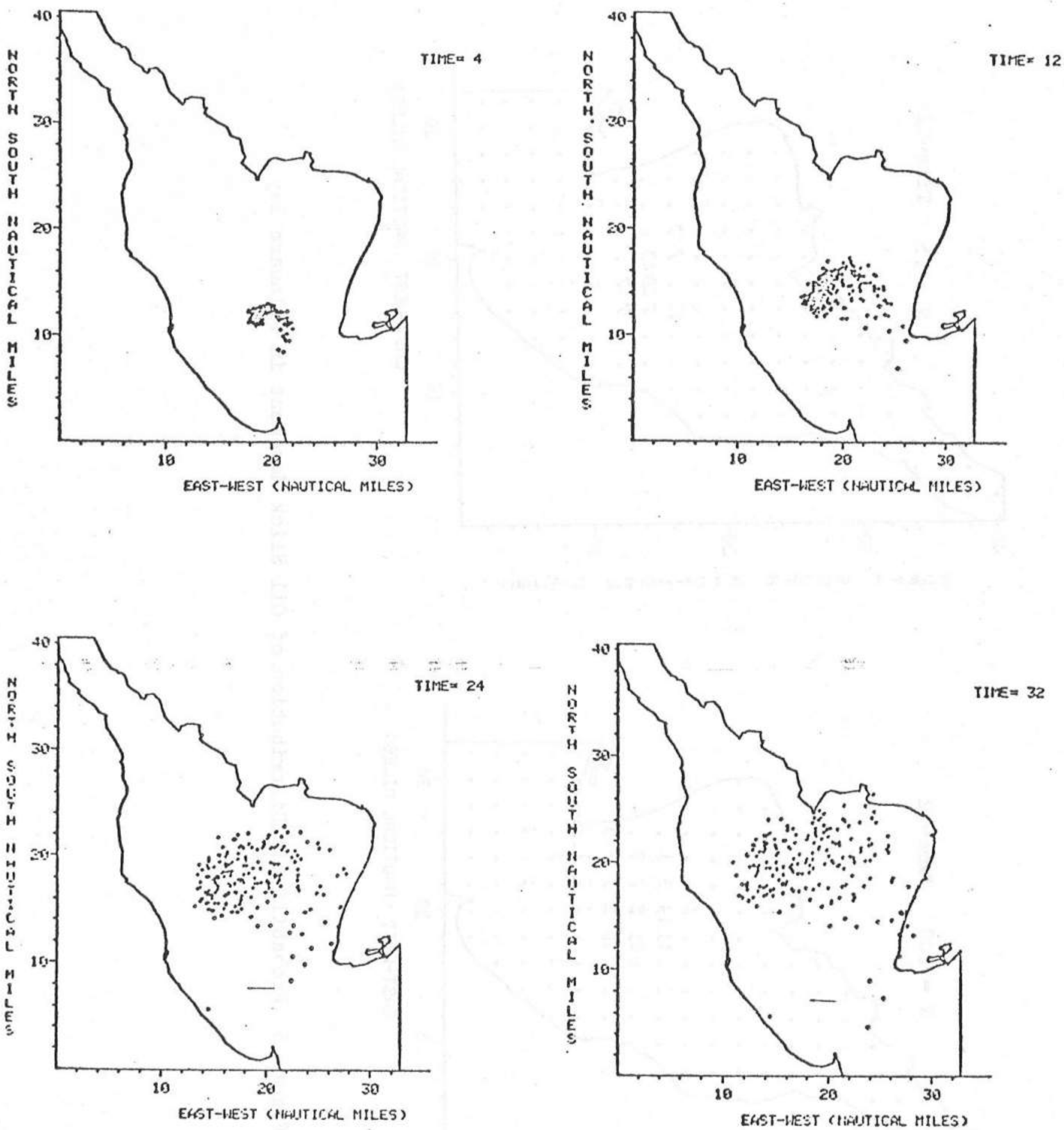


Figure 5 Time Sequence of Oil Slick Drifting (Probabilistic Model)

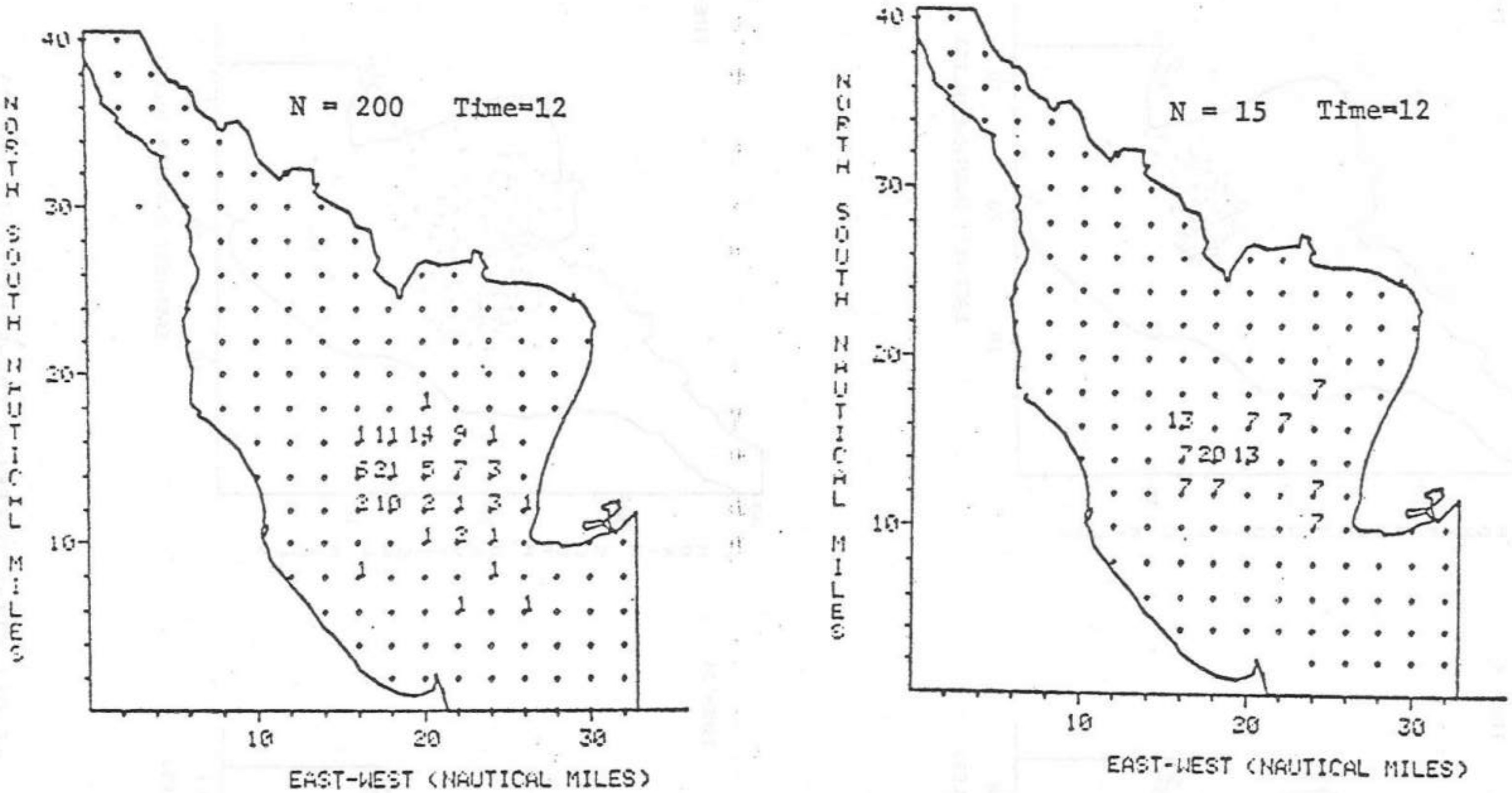
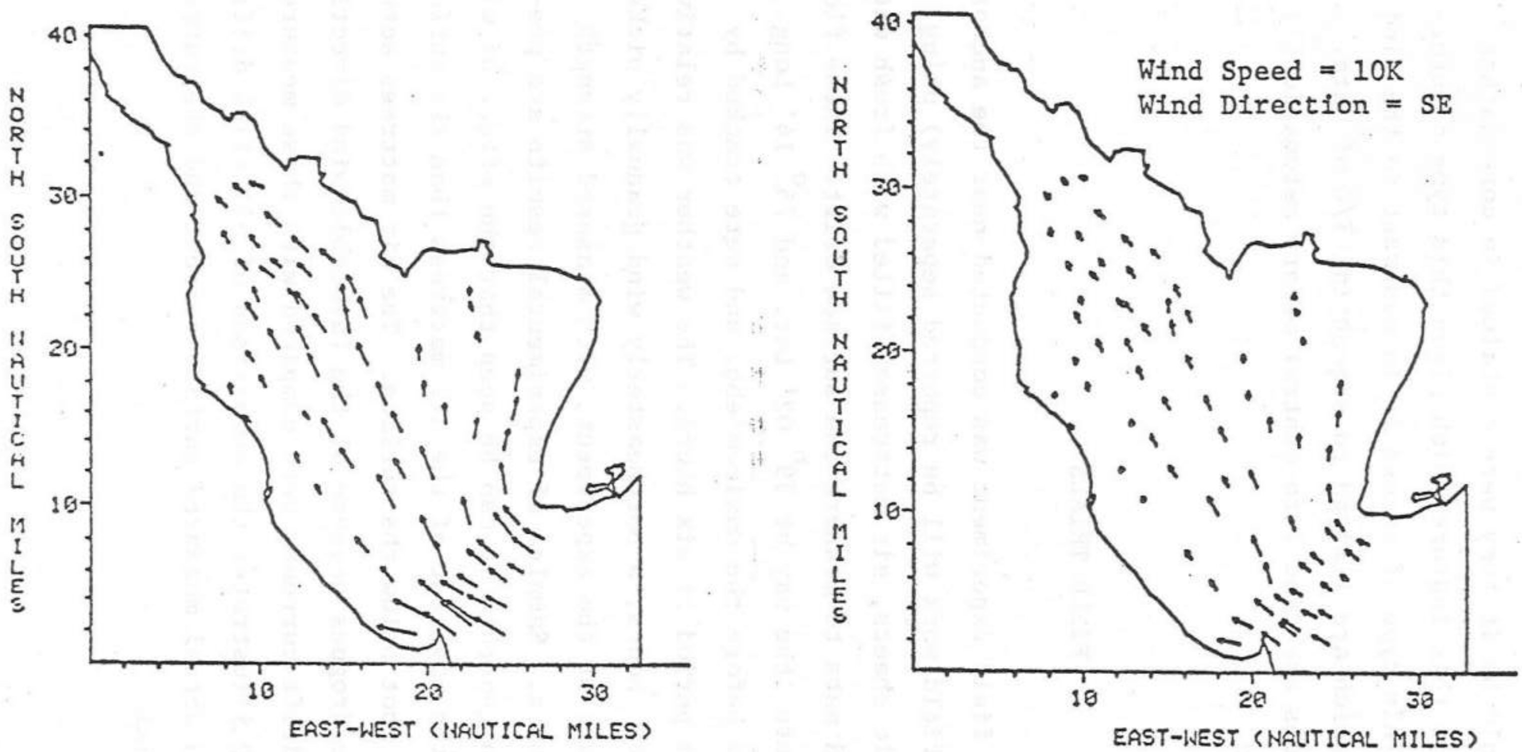


Figure 6 Probabilistic Distribution of Oil Slick Movement in Delaware Bay



Bay Current at Maximum Flood

Oil Drift Current

Figure 7 Mapping of Tidal Current and Effective Oil Drift Current During Maximum Flood in actual application. The Basic-Plus language used in the simulation does this by means of a simple random access file system named virtual core. The elements of data within virtual core are individually addressable as they would be if they were contained in core rather than a disk file. It is this feature which gives this type of storage device its name. This type of access is in contrast to the kind for normal data files which are limited to sequential I/O of data. The virtual core matrices are read into central memory automatically each time they are used.

FIELD TRIALS

On May 8, 1975, a field experiment was conducted near the anchorage area (details of this field work will be reported separately) using surface drogues, plastic sheets, air mattresses filled with fresh water, and articulated plywood mats to measure the surface drift. These floating objects were dropped into the bay at 39° 02' Lat. and 75° 14' Long. approximately two hours before the maximum ebb, and were tracked by boat and airplane for a period of six hours. The weather was relatively calm during the first two hours; a northeasterly wind gradually picked up during the latter part of the experiment, with measured strength varying from 5 to 15 knots. Samples of experimental results are presented in Figure 8. In general, it can be seen that the effect of wind is more pronounced on the movement of the air mattress than the surface drogues which were one foot below the surface. The air mattress actually drifted faster than the drogues because of the favorable wind direction. The predicted surface drift currents were compared with those measured in Figure 9. Figure 10 illustrates the comparison of oil slick drift as predicted, using the actual measured surface current and the current data built into the model.

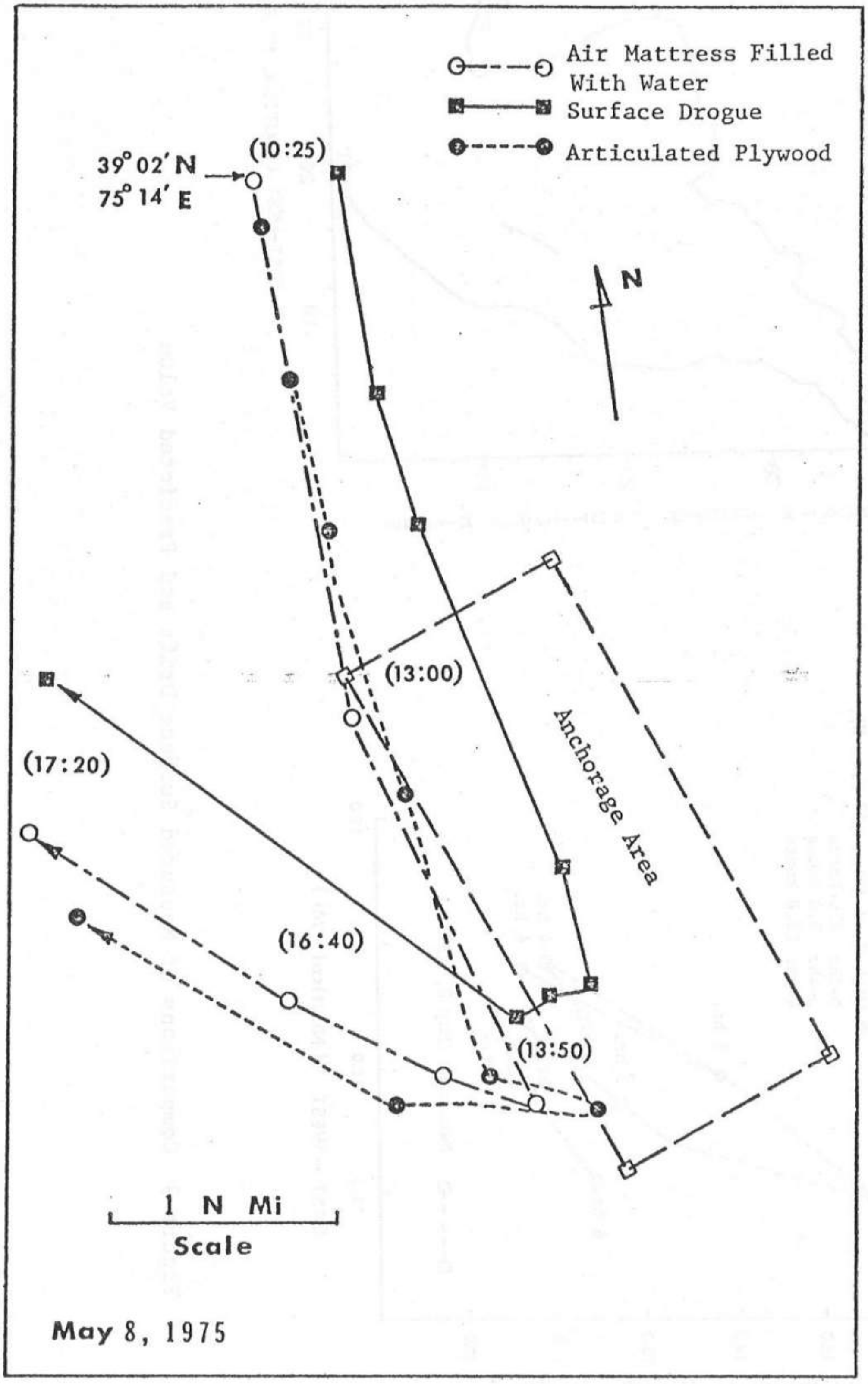


Figure 8 Surface Current Measurement Using Various Floating Objects

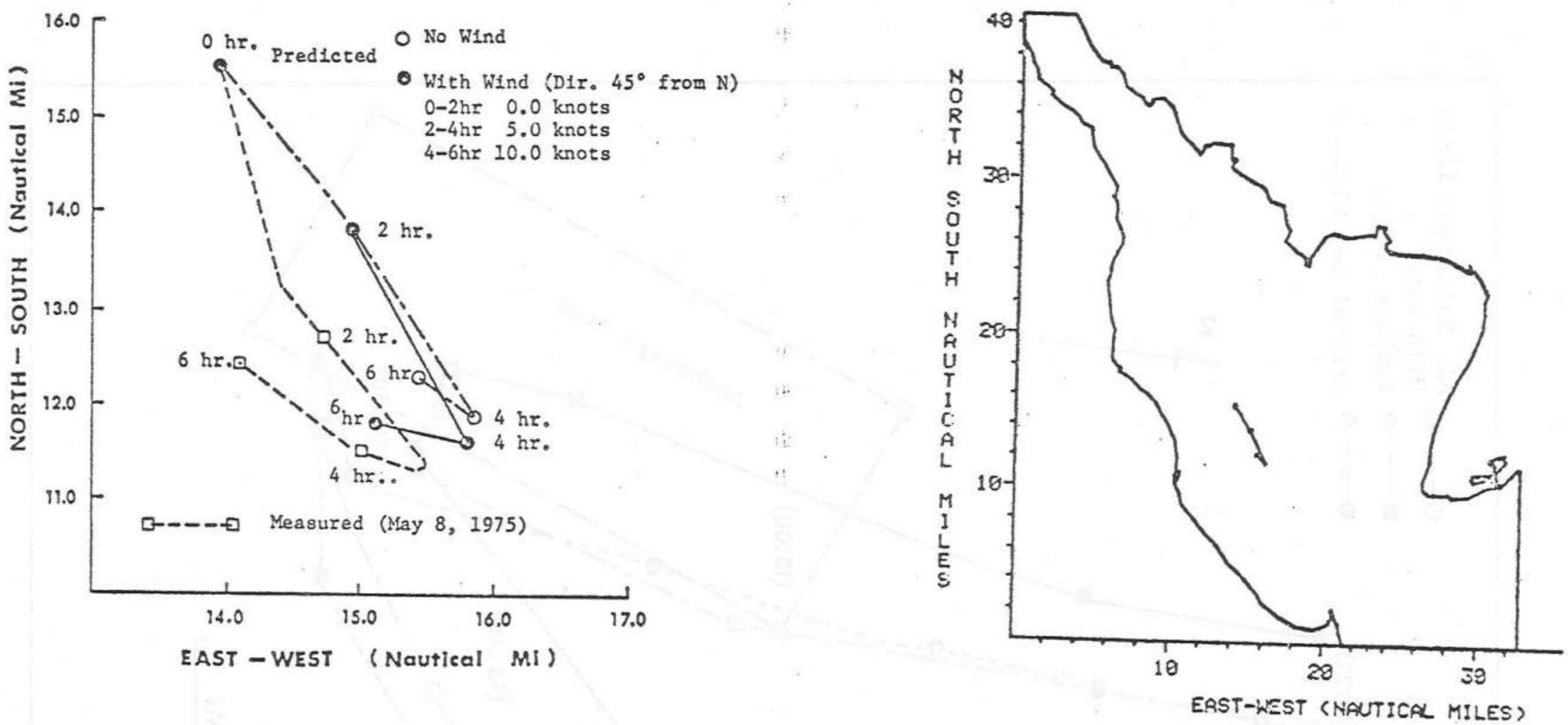


Figure 9 Comparisons of Measured Surface Drift and Predicted Value

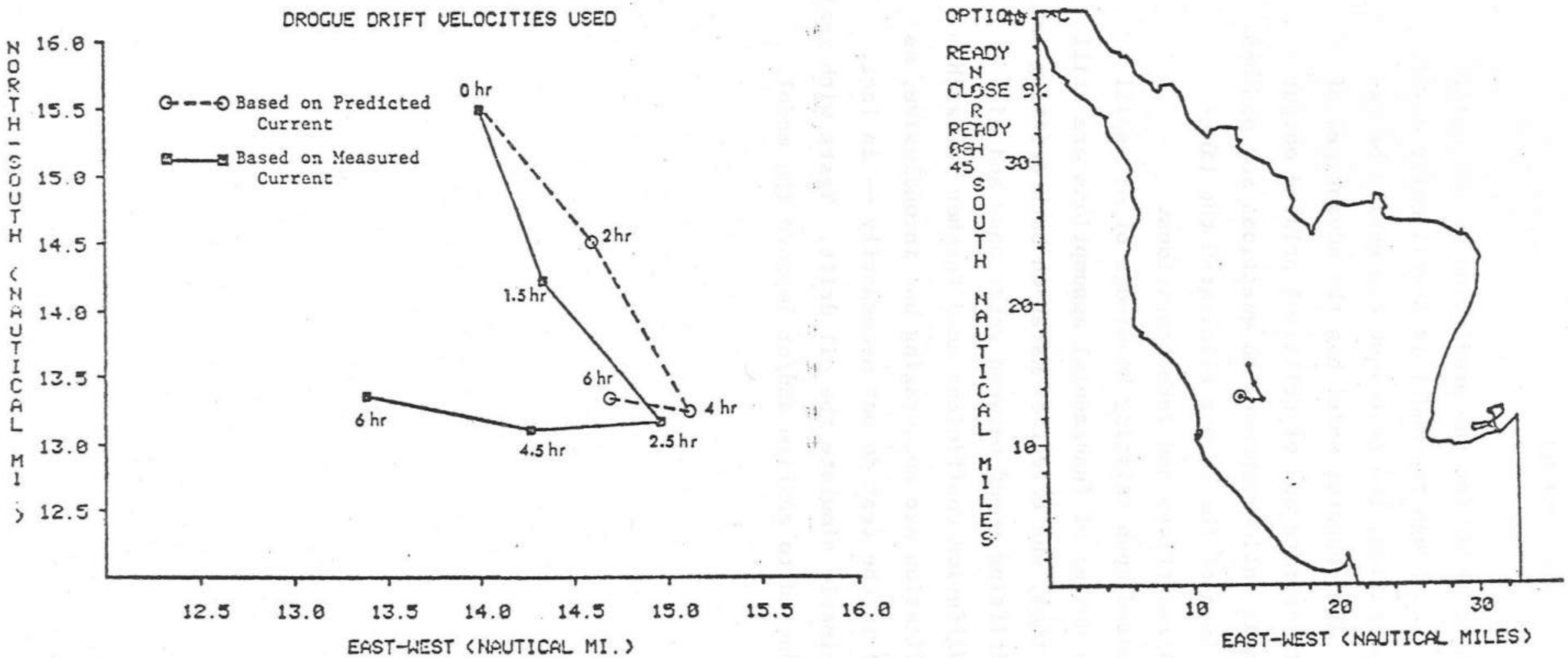


Figure 10 Example of Oil Slick Prediction by the Model, Using Measured Current Information

CONCLUSIONS

An interactive computer model for the prediction of oil spill dispersion was developed. Although the model is specifically developed for Delaware Bay application, the technique can easily be extended to other regions. The computer model has the advantages of being relatively simple to operate and of utilizing printed output to instruct the user to make valid responses to questions and options. In addition, the graphic form of the output eliminates the time-consuming process of data reductions and interpretations.

Since the model is based upon existing knowledge of oil spill drifting and spreading, a number of fundamental assumptions are still open to question. Among them, the effect of waves on both drifting and spreading, the relative drifting speed between water mass and oil slick, and the value of diffusion coefficient need further research. The results of field verfication are encouraging but inconclusive, as the floating objects used in the test do not necessarily -- in fact, they probably do not -- closely simulate the oil drift. Tests with real oil slicks should be conducted to confirm and/or improve the model.

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APPENDIX I

COMPUTER PROGRAM

VARIABLES

CS()	CHARACTER STRING CONTAINING TITLES OF VARIOUS TIDAL PHASES
C1	TIME SERIES RANDOM NUMBER COEFFICIENT FOR WIND SPEED
C1%	INFORMATION ON CURRENT PHASE
C1%()	TEMPORARY STORAGE ARRAY FOR TIDAL CURRENTS
C2	TIME SERIES RANDOM NUMBER COEFFICIENT FOR WIND DIRECTION
C3	EFFECTIVE WIND SPEED
C4	EFFECTIVE WIND DIRECTION
D	DISTANCE TO CLOSEST CURRENT LOCATION FROM PRESENT PARTICLE LOCATION
D1	GRID X SPACING IN MILES
D2	GRID Y SPACING IN MILES
D8	TIME STEP IN HOURS
D9	TOTAL SIMULATION TIME IN HOURS
ERL	LINE AT WHICH AN ERROR OCCURS
ERR	TYPE OF ERROR WHICH OCCURS AT LINE NUMBER ERL

Variables (Continued)

FNA%	THIS SUBROUTINE DRAWS AN ARROW AT A SPECIFIED LOCATION
FNC%	SUBROUTINE FOR DRAWING CIRCLES SHOWING APPROXIMATE SIZE OF SPILL
FNI$	INTERACTIVE READ AND PRINT ROUTINE
FNP$	LINE DRAWING SUBROUTINE
FNQ	SUBROUTINE WHICH ALLOWS FOR USE OF EITHER THE ENTERED VALUE OR DEFAULT VALUE IF CARRIAGE RETURN IS ENTERED
FNR	RANDOM NUMBER GENERATING SUBROUTINE
FNT1$	THIS SUBROUTINE DRAWS TICK MARKS ON THE X AXIS
FNT2$	THIS SUBROUTINE DRAWS TICK MARKS ON THE Y AXIS
FNX	THIS SUBROUTINE DRAWS CROSSES WHICH REPRESENT LOCATION OF GRID POINTS
G	GRAVITATIONAL ACCELERATION CONSTANT (32.2 FT/SEC**2)
G%	DECISION VARIABLE TO DRAW OR NOT DRAW GRID POINTS
L$	VARIABLE TYPED IN BY OPERATOR TO SIGNIFY OPTION CHOSEN
M	ABSOLUTE VISCOSITY OF WATER (FT**2/SEC)
N%	NUMBER OF DATA POINTS (I.E. X & Y LOCATIONS) OF THE BAY OUTLINE
N%()	TOTAL NUMBER OF EXPERIMENTS WHICH END UP IN THE VICINITY OF A PARTICULAR GRID POINT

Variables (Continued)

N1%	TOTAL NUMBER OF EXPERIMENTS TO BE SIMULATED
O%	VARIABLE WHICH DETERMINES LOGIC FOR EITHER INPUT OR OUTPUT
PI	THE CONSTANT 3.1415926(ETC.)
R	RANDOM NUMBER WITH A MEAN OF 0.5
R0	CALCULATED APPROXIMATE RADIUS OF THE OIL SLICK
R2	DIFFERENCE IN THE DENSITY BETWEEN OIL AND THAT OF WATER (SLUGS/FT**3)
R3	DENSITY OF OIL (SLUGS/FT**3)
R4	DENSITY OF WATER (SLUGS/FT**3)
S	SCALE FACTOR TO GET FROM MILES TO INCHES ON THE TEKTRONIX SCREEN
S1	OFFSET IN X DIRECTION FROM CORNER OF DISPLAY TO COORDINATE ORIGIN
S2	OFFSET IN Y DIRECTION FROM CORNER OF DISPLAY TO COORDINATE ORIGIN
S3	SURFACE TENSION (LBS./FT.)
T	TIME ELAPSED SINCE SPILL OCCURRED (IN SECONDS)
TS	LABEL FOR VERTICAL AXIS
T1	CUMULATIVE VARIABLE PHYSICAL TIME OF SIMULATION
T1%	DESCRIPTOR VARIABLE CONTAINING TIDAL CURRENT PHASE

Variables (Continued)

V	VOLUME OF OIL SPILL (FT**3)
V1	TIME AT WHICH GRAVITY-INERTIAL MECHANISM ENDS AND GRAVITY-VISCOUS REGIME BEGINS
V2	TIME AT WHICH GRAVITY-VISCOUS REGIME ENDS AND TURBULENT SPREADING BEGINS
W	WEIGHT OF SIMULATED OIL SPILL (TONS)
W()	ARRAY CONTAINING PREDICTIVE WIND SPEED AND DIRECTION ENTERED BY OPERATOR
X$	VARIABLE C, G, OR E WHICH MAY BE ENTERED BY OPERATOR WHEN INSTRUCTION "TYPE RETURN TO CONTINUE:" IS PRINTED BY PROGRAM AFTER GRAPHICS HAVE TERMINATED. (C=DRAW CURRENTS, G=DRAW GRID LOCATIONS, E=DRAW EXPERIMENT LOCATIONS)
XØ	INITIAL X LOCATION OF THE PARTICLE
X1()	TEMPORARY TIME SERIES VALUES OF PREVIOUS WIND SPEEDS
X2	X COORDINATE OF THE GRID POINT BEING DRAWN
X2()	TEMPORARY TIME SERIES VALUES OF PREVIOUS WIND DIRECTIONS
X3	X POSITION ON THE SCREEN OF THE PROBABILITY OF AN EXPERIMENT BEING FOUND IN THE VICINITY OF THAT GRID POINT
YØ	INITIAL Y LOCATION OF THE PARTICLE
Y2	Y COORDINATE OF THE GRID POINT BEING DRAWN
Y3	Y POSITION ON THE SCREEN OF THE PROBABILITY OF AN EXPERIMENT BEING FOUND IN THE VICINITY OF THAT GRID POINT

FILE IDENTIFICATIONS

KB	= FILE 1%	THIS IS THE KEYBOARD FROM WHICH RESPONSES ARE ENTERED. IT MAY OR MAY NOT BE THE TERMINAL FROM WHICH THE GRAPHICAL RESULTS ARE OBTAINED.
"OILSPL.TS1"	= FILE 2% = X1%(500)	VIRTUAL ARRAY WHICH CONTAINS THE X ORDERED LOCATIONS OF THE DIFFERENT EXPERIMENTS.
"OILSPL.TS2"	= FILE 3% = Y1%(1500%)	VIRTUAL ARRAY WHICH CONTAINS THE Y ORDERED LOCATIONS OF THE DIFFERENT EXPERIMENTS.
"OILSPL.WDS"	= FILE 4% = W1(500%,3%)	VIRTUAL ARRAY WHICH CONTAINS THE WIND SPEED FOR THE VARIOUS TIME STEPS. THE SECOND ARGUMENT OF THE ARRAY IS FOR THE PREVIOUS TIME STEP WHICH IS BEING CORRELATED.
"OILSPL.WDD"	= FILE 5% = W2(500%,3%)	VIRTUAL ARRAY WHICH CONTAINS THE WIND DIRECTIONS FOR THE VARIOUS TIME STEPS. THE SECOND ARGUMENT OF THE ARRAY IS FOR WHICH OF THE PREVIOUS TIME STEPS THE VARIABLE STANDS.

<u>File Identifications (Continued)</u>

"OILSPL.CUR" = FILE 6%	= C%(768%,3%)	VIRTUAL ARRAY WHICH CONTAINS ALL THE CURRENT INFORMATION. THE SECOND ARGUMENT OF THE ARRAY SIGNIFIES WHETHER THE VARIABLE IS FOR THE X LOCATION, THE Y LOACTION, THE CURRENT MAGNITUDE OR THE CURRENT DIRECTION.
"OILSPL.DAG" = FILE 7%	= A1(40%,36%)	VIRTUAL ARRAY CONTAING DEFLECTION ANGLES FOR VARIOUS PART OF THE BAY DEPENDENT UPON THE LOCAL DEPTH OF THE BAY AT THAT LOCATION.
KB3J = FILE 10%		TEKTRONIX DISPLAY UPON WHICH GRAPHICAL RESULTS ARE DISPLAYED.
"X .PTS" = FILE 11%	= X(512%)	VIRTUAL ARRAY CONTAINING THE ORDERED X BOUNDARIES OF THE BAY.
"Y .PTS" = FILE 12%	= Y(512%)	VIRTUAL ARRAY CONTAINING THE ORDERED Y BOUNDARIES OF THE BAY.

MAIN PROGRAM

```
10 !**********  SET UP THINGS THAT HAPPEN ONLY ONCE  **************************
15 OPEN "KB:" AS FILE 1% : OPEN "X.PTS" FOR INPUT AS FILE 11% : OPEN "Y.PTS"
       FOR INPUT AS FILE 12% : DIM #11%,X(512%) : DIM #12%,Y(512%) : N%=X(0%)
20 E0=10. : G=32.2 : R3=1.746 : R4=1.94 : R2=R4-R3 : S3=7.55E-4
       : M=2.85E-5      !CONSTANTS FOR CALCULATING SIZE OF SPILL
25 OPEN "KB40:" FOR OUTPUT AS FILE #10%
27 OPEN "PTS113.DAT" FOR OUTPUT AS FILE #9%
28 PRINT #9%,"#WIND @ 5KTS, FROM 45 DEG" :
       PRINT #9%,"#EAST-WEST (NAUTICAL MI.)" :
       PRINT #9%,"#NORTH-SOUTH (NAUTICAL MI.)":
       PRINT #9%,"#L"
29 PRINT #9%,"12,16" :
       PRINT #9%,"12,10" : PRINT #9%,"18,10" : PRINT #9%,"#B1" : PRINT #9%,"14,
15.5"
30 OPEN "OILSPL.TS1" FOR OUTPUT AS FILE 2% : DIM #2%,X1%(500) :
       KILL "OILSPL.TS1" : OPEN "OILSPL.TS2" FOR OUTPUT AS FILE 3% :
       DIM #3%,Y1%(1500%) : KILL "OILSPL.TS2" : OPEN "OILSPL.WDS"
       FOR OUTPUT AS FILE 4% : DIM #4%,W1(500%,3%) : KILL "OILSPL.WDS" :
       OPEN "OILSPL.WDD" FOR OUTPUT AS FILE 5% : DIM #5%,W2(500%,3%) :
       KILL "OILSPL.WDD" : OPEN "OILSPL.CUR" FOR INPUT AS FILE 6% :
       DIM #6%,C%(768%,3%) : OPEN "OILSPL.DAG" FOR INPUT AS FILE 7% :
       DIM #7%,A1(40%,36%) : R1=5 : T5=PI/8 : M9=2^31
35 DIM G1%(50%,10%),G%(50%),C1%(80%,3%),X1(4%),X2(4%),C$(5%),N%(20%,16%),
       W(20%,1%) : C$(0%)="MAX FLOOD" : C$(1%)="2 HR. AFTER MAX FLOOD" :
       C$(2%)="2 HR. BEFORE MAX EBB" : C$(3%)="MAX EBB" :
       C$(4%)="2 HR. AFTER MAX EBB" : C$(5%)="2 HR. BEFORE MAX FLOOD"
40 C1=SQR(4*3*14.9252) : C2=SQR(4*3*.5877) : X1%(500%)=0% : Y1%(500%)=0% :
       W1(500%,3%)=0% : W2(500%,3%)=0%
```

Main Program(Continued)

```
45 S1=100 : S2=100 : M1=-1E6 : M2=-1E6 : M3=1E6 : M4=1E6 : FOR X%=1% TO N% :
       M1=X(X%) IF X(X%)>M1 : M2=Y(X%) IF Y(X%)>M2 : M3=X(X%) IF X(X%)<M3 :
       M4=Y(X%) IF Y(X%)<M4 : NEXT X% : S=(780.-S2)/(M2-M4)
50 !
   !!!!!!!!!!!  START OF PROGRAM ALL THAT PRECEEDES IS JUNK  !!!!!!!!!!!!!!!
   !
55 !**********  ASK ALL QUESTIONS TO FIND OUT WHERE TO GO  *****************
60 GO SUB 3190 : Z%=0% : UNTIL Z% : D1=0 : D2=0 : X0=-1 : Y0=-1 : D9=-1 :
       D8=-1 : C1%=-1% : N1%=-1% : P1%=675% : P2%=700% : R8=65539
65 O%=0% : O%=VAL(FNI$("OPTION"))+1% WHILE O%<1% OR O%>5% : ON O% GO SUB
       75,90,95,460,85 : NEXT : GO TO 9990
70 !**********  SUBROUTINES TO HANDLE DIFFERNET OPTIONS  ********************
75 PRINT #1%,"1-SIMULATION WITH WIND SPEED AND DIRECTION GENERATED BY ";
       "TIME SERIES" : PRINT #1%,"2-SIMULATION WITH WIND SPEED AND ";
       "DIRECTION ENTERED BY OPERATOR"
80 PRINT #1%,"3-DRAW BAY CURRENTS" : PRINT #1%,"4-STOP THE RUN" : RETURN
85 Z%=-1% : RETURN
90 GO SUB 110 : GO SUB 205 : GO SUB 3190 : RETURN
95 GO SUB 110 : GO SUB 365 : GO SUB 3230 : GO SUB 3190 : RETURN
100 !
   !!!!!!!!!!!  INTERACTIVE STUFF AND GRID POINT CALCULATIONS  !!!!!!!!!!!!!
   !
105 !**********  ASK PARTICULAR TYPE QUESTIONS  ******************************
110 D1=FNQ("GRID X SPACING",2,"MI") WHILE D1<.5 OR D1>10 :
       D2=FNQ("GRID Y SPACING",2,"MI") WHILE D2<.85 OR D2>10 :
       X0=FNQ("SPILL X LOCATION",20,"MI") WHILE X0<0 OR X0>32 :
       Y0=FNQ("SPILL Y LOCATION",10,"MI") WHILE Y0<0 OR Y0>40
115 D9=FNQ("TOTAL TIME",12,"HRS") WHILE D9<0 OR D9>48 :
       D8=FNQ("TIME STEP",2,"HRS") WHILE D8<2 OR D8>8
120 C1%=FNQ("INITIAL CURRENT (0,1,2,3,4,5)",0,"") WHILE C1%<0% OR D1%>5% :
       C1%=C1%*128% : W=FNQ("SIZE OF SPILL",1000,"TONS")*2000 :
       C5=.56*D8 : V=W/(R3*G)
```

Main Program(Continued)

```
125 IF FNIS("DRAW GRID POINTS")="YES" THEN G%=-1% ELSE G%=0%
130 O%=VAL(FNIS("OUTPUT OPTION")) : IF O% THEN 140 ELSE
       PRINT #1%,"1-DRAW EXPERIMENT LOCATIONS" :
       PRINT #1%,"2-TRACE AVERAGE CENTERS" :
       PRINT #1%,"3-DRAW CIRCLES AROUND AVERAGE CENTERS SHOWING DIFFUSION"
135 PRINT #1%,"4-SHOW PROBABILTIY AT GRID POINTS (2-MI SPACING ONLY)" :
       GO TO 130
140 GO TO 130 IF O%<1% OR O%>4% : IF O%=4% THEN D1=2 : D2=2
145 !**********  SET UP CRITICAL TIMES FOR THE DIFFUSION STUFF  **************
150 V1=(.98*(R3^(1/6))*(V^(1/12))/(1.14*M^(1/12))*(G^(1/12)*(R2^(1/12))))^4
       : V2=(.98*(V^(1/3))*((M*R2*R3*G)^(1/6))/(1.6*SQR(S3)))^2
155 !**********  ZERO ARRAYS TO FIGURE OUT GRID POINTS  **********************
160 G%(X%)=0% FOR X%=0% TO 50% : G1%(X%,X1%)=0% FOR X1%=0% TO 10% FOR X%=0%
       TO 50%
165 !**********  FIGURE OUT WHERE TO PUT THE GRID POINTS  *******************
170 X1=X(1%) : Y1=Y(1%) : FOR X%=2% TO N% : X2=X(X%) : Y2=Y(X%) : F%=2*(Y1<Y2)
       +1% : N2%=INT(Y1/D2+1E-10*F%) : N2%=N2%+1% IF F%=-1% : D3=N2%*D2
175 WHILE Y1<=D3 AND Y2>D3 OR Y1>D3 AND Y2<=D3 : G1%(N2%,G%(N2%))=((D3-Y1)*
       (X1-X2)/(Y1-Y2)+X1)*10 : G%(N2%)=G%(N2%)+1% : N2%=N2%-F% : D3=D2*N2% :
       NEXT : Y1=Y2 : X1=X2 : NEXT X%
180 !**********  SORT OUT THE GRID POINT ARRAY  ******************************
185 FOR X%=0% UNTIL G%(X%)=0%
190 F%=0% : FOR X1%=0% TO G%(X%)-2% : IF G1%(X%,X1%)>G1%(X%,X1%+1%) THEN T%=
       G1%(X%,X1%) : G1%(X%,X1%)=G1%(X%,X1%+1%) : G1%(X%,X1%+1%)=T% : F%=-1%
195 NEXT X1% : GO TO 190 IF F% : NEXT X% : RETURN
200 !
    !!!!!!!!!!!!  TIME SERIES METHOD  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
    !
205 N1%=FNQ("NO. OF EXPERIENTS",15,"") WHILE N1%<3% OR N1%>500%
```

Main Program (Continued)

```
210 !*********** CALL INITIAL SET UP ROUTINES FOR OUTPUT ******************
215 ON O% GO SUB 495,505,505,495
220 !*********** INITIALIZE TIME SERIES ************************************
225 MAT X1=ZER : MAT X2=ZER : FOR I%=1% TO 100% : R=RND-.5 :
      U1=.9422*X1(4%)-.1343*X1(2%)+.0765*X1(1%)+C1*R :
      U2=.8982*X2(4%)-.3049*X2(2%)+.2031*X2(1%)+C2*R
230 X1(J%-1%)=X1(J%) FOR J%=2% TO 4% : X1(4%)=U1 :
      X2(J%-1%)=X2(J%) FOR J%=2% TO 4% : X2(4%)=U2 : NEXT I%
235 FOR I%=1% TO N1% : R=RND-.5 :
      U1=.9422*X1(4%)-.1343*X1(2%)+.0765*X1(1%)+C1*R :
      U2=.8982*X2(4%)-.3049*X2(2%)+.2031*X2(1%)+C2*R
240 FOR J%=1% TO 4% : W1(I%,J%-1%)=X1(J%) : W2(I%,J%-1%)=X2(J%) : NEXT J% :
      FOR J%=2% TO 4% : X1(J%-1%)=X1(J%) : X2(J%-1%)=X2(J%) : NEXT J% :
      X1(4%)=U1 : X2(4%)=U2 : NEXT I%
245 !*********** INITIALIZE PARTICAL LOCATIONS *****************************
250 FOR I%=0% TO N1% : X1%(I%)=10*X0 : Y1%(I%)=10*Y0 : NEXT I%
255 !*********** MOVE PARTICLES IN STEPS OF D8 HOURS FOR D9 HOURS ***********
260 T2%=-1% : FOR T1=D8 TO D9 STEP D8
265 !*********** LOAD THE RIGHT CURRENT ARRAY *******************************
270 T1%=128%*(T1/2)+C1% : T1%=T1%-768% WHILE T1%>=768% : IF T1%<>T2% THEN
      C1%(0%,X%)=C%(T1%,X%) FOR X%=0% TO 4%*C%(T1%,0%) : T2%=T1%
275 !*********** MOVE ALL THE PARTICLES ONE AT A TIME ***********************
280 FOR K1% = 1% TO N1%
285 IF X1%(K1%)<0% THEN 345     !IF PARTICLE NOT IN BAY THEN SKIP IT
290 !*********** FIND THE RIGHT CURRENT VECTOR *****************************
295 X=X1%(K1%)/10. : Y=Y1%(K1%)/10. : D=1E5 : FOR I%=1% TO C1%(0%,0%) :
      X1=C1%(I%,0%)-X : Y1=C1%(I%,1%)-Y : D3=SQR(X1*X1+Y1*Y1) :
      IF D3<D THEN D=D3 : K%=I%
300 NEXT I%
305 !*********** DO ALL THE TIME SERIES STUFF ******************************
310 R=RND-.5 : U1=.9422*W1(K1%,3%)-.1344*W1(K1%,1%)+.0765*W1(K1%,0%)+C1*R :
```

Main Program(Continued)

```
      U2=.8982*W2(K1%,3%)-.3049*W2(K1%,1%)+.2031*W2(K1%,0%)+C2*R
315 W1(K1%,0%)=W1(K1%,1%) : W1(K1%,1%)=W1(K1%,2%) : W1(K1%,2%)=W1(K1%,3%) :
      W1(K1%,3%)=U1
320 W2(K1%,0%)=W2(K1%,1%) : W2(K1%,1%)=W2(K1%,2%) : W2(K1%,2%)=W2(K1%,3%) :
      W2(K1%,3%)=U2
325 !**********  MOVE THE PARTICLE NOW  ***********************************
330 C3=(.8256+.03*D8*U1)*10. : C4=3.3+U2-A1(X1%(K1%)/10%,Y1%(K1%)/10%) :
      X1%(K1%)=X1%(K1%)-C3*SIN(C4)+C5*C1%(K%,2%) :
      Y1%(K1%)=Y1%(K1%)-C3*COS(C4)+C5*C1%(K%,3%)
335 !**********  CHECK IF ITS IN THE BAY IF NOT THEN MARK IT  ****************
340 IF Y1%(K1%)<0% THEN X1%(K1%)=-X1%(K1%) IF X1%>0% ELSE T%=0% :
      Y%=Y1%(K1%)/10%/D2 : T%=-1% IF X1%(K1%)>G1%(Y%,I%) AND
      X1%(K1%)<G1%(Y%,I%+1%) FOR I%=0% TO G%(Y%) STEP 2% :
      X1%(K1%)=-X1%(K1%) UNLESS T%
345 N9%=N9%+1% IF X1%(K1%)>0% : NEXT K1% : IF N9%<3% THEN PRINT #10%,
      RECORD 1%,CHR$(29%);FNP$(200%,744%);CHR$(31%);
      "NO. OF EXPS.<3 AT";T1;"HRS"; : GO SUB 3230 : RETURN
350 ON O% GO SUB 530,540,560,567 : NEXT T1 : X%=FNC%(S*R0/6080.27,S*X0+S1,
      S*Y0+S2) IF O%=2% : GO SUB 3230 IF O%=2% OR O%=3% : RETURN
351 RETURN
355 !
    !!!!!!!!!!!  DETERMINISTIC METHOD  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
    !
360 !**********  ASK FOR ALL THE WIND SPEEDS AND DIRECTIONS  ****************
365 GO SUB 3190 : I%=0% : IF FNI$("ALL ZERO")="YES" THEN W(0%,X%)=0
      FOR X%=0% TO 40% : GO TO 380
370 FOR T1=D8 TO D9 STEP D8
375 W(I%,0%)=VAL(FNI$("WIND SPEED AT"+NUM$(T1)+"HRS")) :
      W(I%,1%)=-(VAL(FNI$("WIND DIRECTION AT"+NUM$(T1)+"HRS"))-90)/180*PI :
      I%=I%+1% : NEXT T1
380 GO SUB 505          !GET THE SCREEN SET UP TO DRAW ON
385 !**********  GO THROUGH THE TIME STEPS  **********************************
390 T2%=-1% : J%=0% : FOR T1=D8 TO D9 STEP D8
395 T1%=128%*INT((T1-D8)/2)+C1% : T1%=T1%-768% WHILE T1%>=768% : IF T1%<>T2% THE
N
      C1%(0%,X%)=C%(T1%,X%) FOR X%=0% TO 4%*C%(T1%,0%) : T2%=T1%
```

Main Program(Continued)

```
400 !*********** FIND THE CLOSEST CURRENT ************************************
405 D=1E5 : FOR I%=1% TO C1%(0%,0%) : X1=C1%(I%,0%)/10.-X0 : Y1=C1%(I%,1%)
       /10.-Y0 : D3=SQR(X1*X1+Y1*Y1) : IF D3<D THEN D=D3 : K%=I%
410 NEXT I%
415 !*********** MOVE THE PARTICLE *****************************************
420 X0=X0-.03*D8*W(J%,0%)*COS(W(J%,1%))+C5*C1%(K%,2%)/10. :
       Y0=Y0-.03*D8*W(J%,0%)*SIN(W(J%,1%))+C5*C1%(K%,3%)/10.
422 PRINT #9%,X0,",",Y0
423 PRINT "HERE IS THE CURRENT"
424 FOR I%=0% TO 3% : PRINT C1%(K%,I%), : NEXT I% : PRINT
425 !*********** CHECK IF IT IS STILL IN THE BAY IF NOT COMPLAIN ************
430 IF Y0>0 THEN Y%=Y0/D2 : T%=0% : T%=-1% IF X0*10>G1%(Y%,I%) AND
       X0*10<G1%(Y%,I%+1%) FOR I%=0% TO G%(Y%) STEP 2%
435 IF Y0<0 OR T%=0% THEN PRINT #10%, RECORD 1%,CHR$(29%);
       FNP$(350%,722%);CHR$(31%);"OFF MAP AT";T1;"HRS"; :
       GO SUB 3230 : GO SUB 3190 : RETURN
440 !*********** GO TO PROPER OUTPUT ROUTINE *********************************
445 ON O% GO SUB 600,600,610,600 : J%=J%+1% : NEXT T1 :
       X%=FNC%(S*R0/6080.27,S*X0+S1,S*Y0+S2) IF O%=2% : RETURN
450 !
       !!!!!!!!!!! DRAW THE CURRENT ARROWS !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
       !
455 !*********** FIND OUT THE OPTION AND GIVE SOME HELP ***********************
460 IF FNI$("DO YOU WANT TO SEE ALL THE CURRENTS")="YES" THEN 485 ELSE
       PRINT #1%,"THE CURRENTS ARE:" : PRINT #1%,
       CVT$$(NUM$(X%),2%);"-";C$(X%) FOR X%=0% TO 5%
465 !********** DO THE ONE AT A TIME STUFF ***********************************
470 T1%=-1% : T1%=VAL(FNI$("WHICH ONE")) WHILE T1%<0% OR T1%>5% :
       T1%=T1%*128% : GO SUB 487 : GO SUB 3190 : GO SUB 3020 :
       GO SUB 3070 : GO SUB 3100
475 PRINT #10%, RECORD 1%,CHR$(29%);FNP$(300%,700%);CHR$(31%);
       "BAY CURRENTS AT "+C$(T1%/128%); : GO SUB 3150 : GO SUB 3230 :
       GO SUB 3190 : IF FNI$("TYPE YES TO SEE MORE CURRENTS")="YES" THEN
       470 ELSE GO SUB 3190 : RETURN
480 !*********** SHOW ALL THE CURRENTS IN ORDER *******************************
```

Main Program(Continued)

```
485 GO SUB 487 ! FOR T1%=0% TO 640% STEP 128% ! GO SUB 3190 ! GO SUB 3020 !
      GO SUB 3070 ! GO SUB 3100 ! PRINT #10%, RECORD 1%,CHR$(29%);
      FNP$(300%,700%);CHR$(31%);"BAY CURRENTS AT ";C$(T1%/128%); !
      GO SUB 3150 ! GO SUB 3230 ! NEXT T1% ! GO SUB 3190 ! RETURN
487 X0=0 ! Y0=0 ! C5=1 ! IF FNI$("DO YOU WANT EFFECTIVE CURRENTS")<>"YES"
      THEN RETURN ELSE C5=.58 ! X1=FNQ("WIND SPEED",0,"KNOTS") !
      Y1=FNQ("WIND DIRECTION",0,"DEGREES")
488 Y1=-(Y1-90)/180*PI ! X0=.03*X1*COS(Y1) ! Y0=.03*X1*SIN(Y1) ! RETURN
490 !
    !!!!!!!!!!!  OUTPUT SETUP ROUTINES  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
    !
495 GO SUB 3190 ! RETURN          !NULL SETUP ROUTINE
500 !**********  SET UP THE SCREEN BY CALLING ALL THE RIGHT ROUTINES  ********
505 GO SUB 3190 ! GO SUB 3020 ! GO SUB 3040 ! GO SUB 3070 ! GO SUB 3100 !
      A1=X0*S+S1 ! A2=Y0*S+S2
510 PRINT #10%, RECORD 1%,CHR$(29%);FNP$(P1%,P2%+44%);CHR$(31%);
      " TIME  LAT.   LONG.   RAD.";CHR$(29%);FNP$(P1%,P2%+22%);CHR$(31%);
      "  HRS. DD MM  DD MM   MI.";FNX$(A1,A2);
515 T1=0 ! GO SUB 550 ! GO SUB 3210 ! RETURN
520 !
    !!!!!!!!!!!  OUTPUT ROUTINES FOR THE TIME SERIES MODEL  !!!!!!!!!!!!!!!!!
    !
525 !**********  DRAW BAY AND ALL EXPERIMENT LOCATIONS  *********************
530 GO SUB 3190 ! GO SUB 3020 ! GO SUB 3070 ! GO SUB 3100 !
      GO SUB 3170 ! PRINT #10%, RECORD 1%,CHR$(29%);FNP$(P1%,P2%);
      CHR$(31%);"TIME=";T1; ! GO SUB 3230 ! RETURN
535 !**********  DRAW LOCUS OF CENTERS  **************************************
540 GO SUB 625           !ENTER HERE FOR TIME SERIES OUTPUT
545 A1=X0*S+S1 ! A2=Y0*S+S1 ! PRINT #10%, RECORD 1%,FNX$(A1,A2);CHR$(29%);
      FNP$(A1,A2);FNP$(B1,B2);  !DO THIS PART ALWAYS
550 GO SUB 640 ! PRINT #10%, RECORD 1%,CHR$(29%);FNP$(P1%,P2%);CHR$(31%); !
      PRINT #10%, USING " ##.#  ## ##  ## ## ##.##",T1,X1(1%),X1(2%),
      X1(3%),X1(4%),R0/6080.27 ! B1=A1 ! B2=A2 ! P2%=P2%-22% ! GO SUB 3210 !
      RETURN
```

<u>Main Program(Continued)</u>

```
555 !**********  DRAW CIRCLES TO REFLECT DIFFUSION  ***************************
560 GO SUB 625 : GO SUB 550 : X%=FNC%(S*R0/6080.27,S*X0+S1,S*Y0+S1) : RETURN
565 !**********  DRAW BAY AND SHOW PROBABILITIES AT THE GRID POINTS  *********
567 RETURN UNLESS (T1/12)=INT(T1/12)
570 GO SUB 3190 : GO SUB 3020 : GO SUB 3040 : GO SUB 3070 :
      GO SUB 3100 : PRINT #10%, RECORD 1%,CHR$(29%);FNP$(P1%,P2%);CHR$(31%);
      "TIME=";T1;
575 N%(0%,X%)=0% FOR X%=0% TO 320% : N9%=0% : FOR K1%=1% TO N1% :
      IF X1%(K1%)>0 THEN X3=X1%(K1%)/20.+.5 : Y3=Y1%(K1%)/20.+.5 :
      N%(Y3,X3)=N%(Y3,X3)+1% : N9%=N9%+1%
580 NEXT K1% : FOR Y%=0% TO 20% : FOR X%=0% TO 16% : IF N%(Y%,X%) THEN
      PRINT #10%, RECORD 1%,CHR$(29%);FNP$(X%*2*S+S1-14,Y%*2*S+S2);CHR$(31%);
      : PRINT #10%, USING "##",N%(Y%,X%)*100./N9%
585 NEXT X% : NEXT Y% : GO SUB 3230 : RETURN
590 !
    !!!!!!!!!!!!  OUTPUT ROUTINE FOR DETERMINISTIC MODEL  !!!!!!!!!!!!!!!!!!!!
    !
595 !**********  SINGLE PARTICLE OUTPUT TRACING CENTER  **********************
600 GO TO 545
605 !**********  SINGLE PARTICLE OUTPUT WITH DIFFUSION  **********************
610 GO SUB 550 : X%=FNC%(S*R0/6080.27,S*X0+S1,S*Y0+S2) : RETURN
615 !
    !!!!!!!!!!!  CALCULATE THINGS NEEDED FOR THE OUTPUT ROUTINES  !!!!!!!!!!
    !
620 !**********  SUBROUTINE FOR CENTER OF MASS AND STANDARD DEVIATION  *******
625 X0=0 : Y0=0 : X1=0 : Y1=0 : N9%=0% : FOR K1%=1% TO N1% : IF X1%(K1%)>0%
      THEN X=X1%(K1%)/10. : Y=Y1%(K1%)/10. : X0=X0+X : Y0=Y0+Y : X1=X1+X*X :
      Y1=Y1+Y*Y : N9%=N9%+1%
630 NEXT K1% : X1=SQR((N9%*X1-X0*X0)/(N9%-1%)) : Y1=SQR((N9%*Y1-Y0*Y0)/(N9%-1%))
      : X0=X0/N9% : Y0=Y0/N9% : RETURN
635 !**********  CALCULATE RADIUS, DEGREES, AND MINUTES  *********************
640 X1(2%)=2326+Y0 : X1(4%)=4532-X0*5/3.9 : X1(1%)=INT(X1(2%)/60) :
      X1(3%)=INT(X1(4%)/60) : X1(2%)=X1(2%)-60*X1(1%) :
      X1(4%)=X1(4%)-60*X1(3%)
```

Main Program(Continued)

```
645 T=T1*3600 : R9=(V^(1/3))*.98*((G*R2*R3/R4)^(1/6))*(V2^.25)/((R3*M)^(1/12))
650 IF T1<V1 THEN
      R0=(V^(1/3))*1.14*((G*R2/(R3*(V^(1/3))))^.25)*SQR(T) ELSE IF T1<V2 THEN
      R0=(V^(1/3))*.98*((G*R2*R3/R4)^(1/6))*(T^.25)/((R3*M)^(1/12)) ELSE
      R0=2.*SQR(2*E0*(T-V2)+((R9/2)^2))
655 RETURN
660 !
    !!!!!!!!!!!!  ERROR HANDLING ROUTINE  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
    !
1010 IF ERL=65 OR ERL=120 OR ERL=130 OR ERL=205 OR ERL=375 OR ERL=470
      OR ERL=2050 THEN RESUME
1020 IF ERR=11% THEN RESUME 9990
1030 PRINT #1%,CVTS$(RIGHT(SYS(CHR$(6%)+CHR$(9%)+CHR$(ERR)),3%),128%);
      " AT LINE";ERL : STOP
2000 !
    !!!!!!!!!!!!  FUNCTIONS  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
    !
2010 DEF FNP$(X%,Y%)=CHR$(Y%/32% OR 32%)+CHR$(Y% AND 31% OR 96%)+
      CHR$(X%/32% OR 32%)+CHR$(X% AND 31% OR 64%)
2020 DEF FNX$(U,V)=CHR$(29%)+FNP$(U-2,V)+FNP$(U+2,V)+CHR$(29%)+FNP$(U,V-2)+
      FNP$(U,V+2)
2030 DEF FNI$(P$) : PRINT #1%,P$+": "; : INPUT LINE #1%,L$ : FNI$=CVTS$(L$,6%)
      : FNEND
2040 DEF FNQ(Q$,V,D$)
2050 X$=FNI$(Q$+" (DEFAULT="+CVTS$(NUM$(V),6%)+" "+D$+")") :
      IF X$="" THEN FNQ=V ELSE FNQ=VAL(X$)
2060 FNEND
2070 DEF FNT1$(X,Y,F%)=CHR$(29%)+FNP$(X,Y)+FNP$(X,Y-F%)
2080 DEF FNT2$(X,Y,F%)=CHR$(29%)+FNP$(X,Y)+FNP$(X-F%,Y)
2090 DEF FNC%(R,X,Y) : PRINT #10%,RECORD 1%,CHR$(29%); : PRINT #10%,
      RECORD 1%,FNP$(X+R*COS(T),Y+R*SIN(T)); FOR T=0 TO 2*PI+.02
      STEP .25 : FNEND
2100 DEF FNA%(X%,Y%,X1%,Y1%) : X1=X1% : Y1=Y1% : IF X1==0 THEN 2110 ELSE
      T=ATN(Y1/X1) : T=PI+T IF X1<0 : GO TO 2120
2110 T=PI/2 : T=-PI/2 IF Y1<0
```

Main Program(Continued)

```
2120 X1=(X%+X1)/10.*S+S1 : Y1=(Y%+Y1)/10.*S+S1
2130 PRINT #10%, RECORD 1%,CHR$(29%);FNP$(X%/10.*S+S1,Y%/10.*S+S2);
        FNP$(X1,Y1);FNP$(X1-R1*COS(T-T5),Y1-R1*SIN(T-T5));
        FNP$(X1-R1*COS(T+T5),Y1-R1*SIN(T+T5));FNP$(X1,Y1); : FNEND
2140 !********** BETTER THAN BASIC RANDOM NUMBER FUNCTION *****************
2150 DEF FNR : R8=65539*R8/M9 : R8=(R8-INT(R8))*M9 : FNR=R8/M9 : FNEND

3000 !
     !!!!!!!!!!! OFTEN USED SUBROUTINES !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
     !
3010 !********** DRAW THE BAY OUTLINE *************************************
3020 PRINT #10%, RECORD 1%,CHR$(29%); : PRINT #10%, RECORD 1%,
        FNP$((X(X%)-M3)*S+S1,(Y(X%)-M4)*S+S2); FOR X%=1% TO N% : RETURN
3030 !********** DRAW ALL THE GRID POINTS IN ********************************
3040 RETURN UNLESS G%
3050 FOR X%=0% UNTIL G%(X%)=0% : FOR X1%=0% TO G%(X%)-1%
        STEP 2% : FOR X=INT(G1%(X%,X1%)/10./D1-1E-10+1)*D1 TO INT(G1%(X%,
        X1%+1%)/10./D1+1E-10)*D1+D1/10 STEP D1 : PRINT #10%, RECORD 1%,
        FNX$((X-M3)*S+S1,(X%*D2-M4)*S+S2); : NEXT X : NEXT X1% : NEXT X% :
        GO SUB 3210 : RETURN
3060 !********** DRAW AXES AND TIC MARKS ************************************
3070 PRINT #10%, RECORD 1%,CHR$(29%)+FNP$(700%,S2)+FNP$(S1,S2)+FNP$(S1,780.); :
        PRINT #10%, RECORD 1%,CHR$(29%)+FNT1$(S1+X1,S2,5%-(INT(X1/(10*S))
        ==X1/(10*S))*5%); FOR X1=S*2 TO S*33 STEP S*2
3080 PRINT #10%, RECORD 1%,FNT2$(S1,S2+X1,5%-(INT(X1/(10*S))==X1/(10*S))*5%);
        FOR X1=S*2TO S*40 STEP S*2 : GO SUB 3210 : RETURN
3090 !********** PRINT ALL THE LABELS ON THE GRAPH ***************************
3100 PRINT #10%, RECORD 1%,CHR$(29%)+FNP$(S1+X1%*S-25%,S2-35)+CHR$(31%)+
        NUM$(X1%);FOR X1%=10% TO 32% STEP 10%
3110 PRINT #10%, RECORD 1%,CHR$(29%)+FNP$(S1-52,S2+S*X1%-9)+CHR$(31%)+NUM$(X1%);
        FOR X1%=10% TO 40% STEP 10%
3120 PRINT #10%, RECORD 1%,CHR$(29%);FNP$(300,25);CHR$(31%);
        "EAST-WEST (NAUTICAL MILES)";
3130 T$="NORTH SOUTH NAUTICAL MILES" : PRINT #10%, RECORD 1%,CHR$(29%);
        FNP$(25,700);CHR$(31%); : PRINT #10%, RECORD 1%,MID(T$,X%,1%);
        CHR$(8%);CHR$(10%); FOR X%=1% TO LEN(T$) : RETURN
```

Main Program(Continued)

```
3140 !*********  DRAW THE CURRENTS  *******************************************
3145 X0=0 : Y0=0 : C5=1
3150 J%=FNA%(C%(X%,0%),C%(X%,1%),X0+C5*C%(X%,2%),Y0+C5*C%(X%,3%))
       FOR X%=T1%+1% TO C%(T1%,0%)+T1% : RETURN
3160 !**********  PRINT TIC MARKS AT THE LOCATIONS OF ALL THE PARTICLES  ******
3170 PRINT #10%, RECORD 1%,FNX$(ABS(X1%(K1%))/10.*S+S1,Y1%(K1%)/10.*S++S2);
       FOR K1%=1% TO N1% : RETURN
3180 !**********  CLEAR THE SCREEN  ********************************************
3190 PRINT #10%, RECORD 1%,CHR$(155%);CHR$(140%); : SLEEP 2% : RETURN
3200 !**********  RETURN THE CURSOR TO HOME POSITION  *************************
3210 PRINT #10%, RECORD 1%,CHR$(29%);FNP$(0%,775%);CHR$(31%); : RETURN
3220 !**********  SAY TYPE RETURN TO CONTINUE  ********************************
3230 PRINT #1%, RECORD 1%,CHR$(29%);FNP$(300%,678%);CHR$(31%); :
       X$=FNI$("TYPE RETURN TO CONTINUE") : RETURN IF X$=""
3240 X$=MID(X$,1%,1%) : GO TO 3230 UNLESS INSTR(1%,"CGE",X$) :
       ON INSTR(1%,"CGE",X$) GO SUB 3145,3050,3170 : GO TO 3230
9990 PRINT #9%,"#E"
9995 CLOSE N% FOR N%=1% TO 12%              !THATS ALL FOLKS
9999 END
```

Appendix II

by D. F. Polis and S. L. Kupferman

Sources of Inaccuracy and Possibilities for Further Improvement as Related to the Field Program

This appendix deals with the reliability of the model's predictions based on the assumption that the empirical formulae relating oil drift to current velocity and wind speed are correct, but that errors attributable to a lack of knowledge of actual wind and current conditions may occur. In the present formulation of the model, the drift of an oil film is taken to be the vector sum of 56% of the instantaneous current velocity obtained from Tidal Current Charts - Delaware Bay and River plus 3% of the wind velocity adjusted for deflection caused by the earth's rotation. The questions under consideration are then how well can the present model represent wind and current conditions and what are the prospects for further improvement resulting from a moderate amount of additional field work.

Data

In responding to these questions we shall rely on the results of the first year's field work. This includes

(1) Two thirty-day records (October 1974 and May-June 1975) from current meters moored approximately two miles northwest of the ship anchorage area, near the axis of the ship anchorage channel. The shallower current meter was 3m below mean low water; the deeper, 10m below mean low water.

(2) Full tidal cycle current, salinity, and temperature measurements taken at a number of stations on cruises in October 1974 and January and

May 1975. Inter alia are thirty-six hours of hourly current meter profiles (values obtained typically at one-meter intervals on each profile) obtained from a vessel anchored within 200 meters of the moored current meters while the current meters were in place.

(3) A one-month record (October 1975) of wind speed and direction at Brandywine Shoal Light in the center of Delaware Bay.

Currents

With regard to the currents there are two problems to be considered:

(1) How well do the currents predicted in Tidal Current Charts represent the currents actually occurring in the location for which a prediction is available?

(2) How much spatial variation is there in the surface currents between such locations?

In answering the first question, it must be realized that the currents presented in the Tidal Current Charts are based on an average of observation over the upper 20 feet (6m) of the water column.

Comparison of moored current meter data from the three meter deep current meter with data from current meter profiles indicated that the moored current meter was a good indicator of the average velocity of the upper six meters of the water column. Velocities from the 3m current meter were typically within 0.02 knots and 10° of the average velocity over the upper six meters of the water column.

A comparison of measured 6m averaged currents with currents estimated from the Tidal Current Charts indicated that the measured values for that time were higher than the predicted values by about 0.1 knots on flood, and lower by about 0.1 knots on ebb. This would result in a cumulative error in the position of an oil slick estimated by the model that would appreciate at the rate of about 0.6 nautical miles per tidal cycle. In other words the Tidal Current Charts do not predict the net drift correctly.

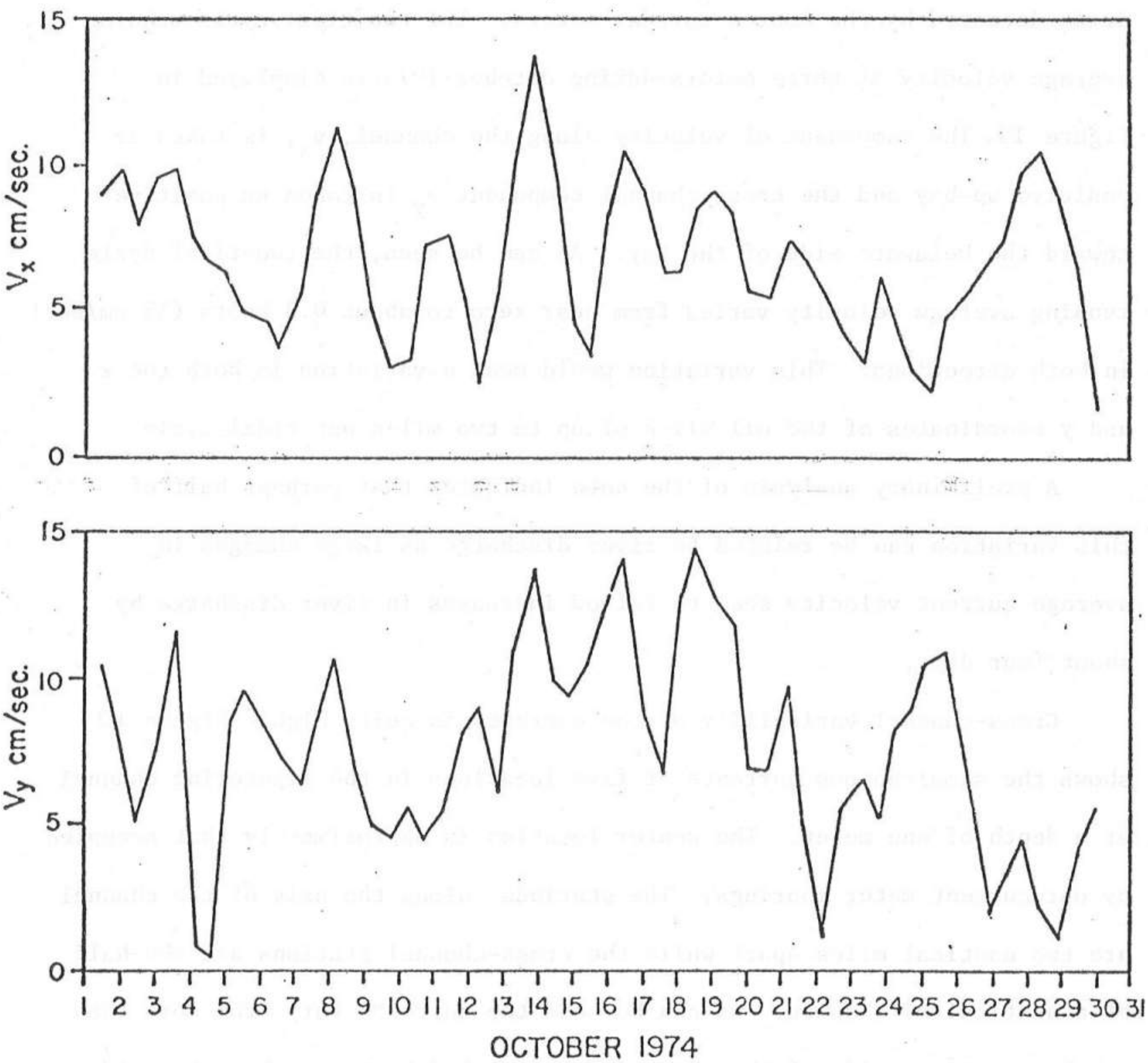
The situation is worse when one considers the long term variations in drift detected by the moored current meters. The two-tidal cycle running average velocity at three meters during October 1974 is displayed in Figure P1. The component of velocity along the channel, ν_x, is taken as positive up-bay and the cross-channel component ν_y is taken as positive toward the Delaware side of the Bay. As can be seen, the two-tidal cycle running average velocity varies from near zero to about 0.3 knots (15 cm/sec) in both directions. This variation would mean a variation in both the x and y coordinates of the oil slick of up to two miles per tidal cycle.

A preliminary analysis of the data indicates that perhaps half of this variation can be related to river discharge as large changes in average current velocity seem to follow increases in river discharge by about four days.

Cross-channel variability of the currents is quite high. Figure P2 shows the simultaneous currents at five locations in the lightering channel at a depth of one meter. The center location is approximately that occupied by our current meter moorings. The stations along the axis of the channel are two nautical miles apart while the cross-channel stations are one-half of a nautical mile apart. As can be seen the currents vary from more than two knots on one side of the channel to about 0.2 knots on the other side of the channel, while the tidal current charts fail to indicate any cross channel variability. This kind of cross-channel variation will result in variations of oil movement accumulating at the rate of about one nautical mile

FIGURE P1

2-TIDAL CYCLE RUNNING AVERAGE CURRENT
UPPER CURRENT METER



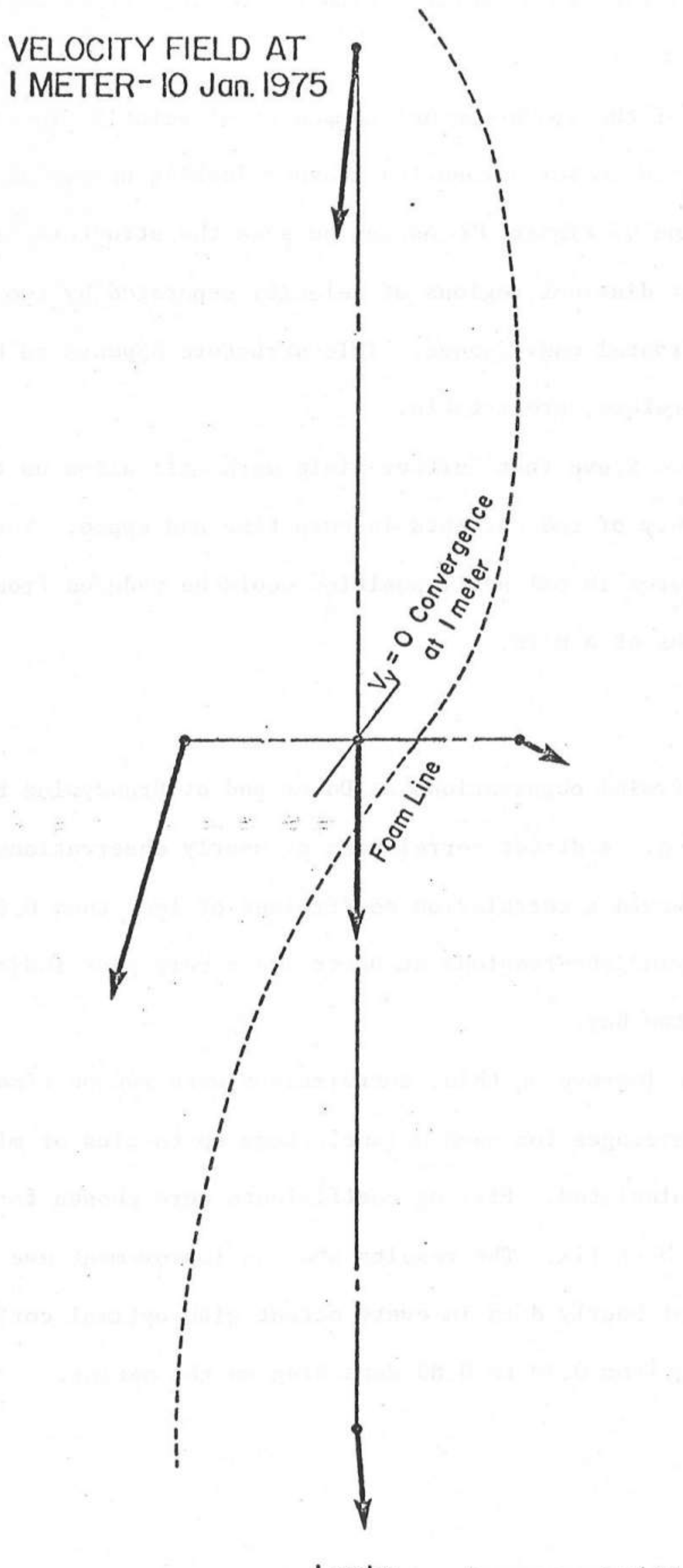

VELOCITY FIELD AT
I METER- 10 Jan. 1975
V_y = O Convergence
at I meter
Foam Line
I meter
1115
= I kt.

FIGURE P2

per hour. This variation is associated with the passage of estuarine fronts.

The structure of the cross-channel component of velocity is illustrated in Figure P3. This is a sector across the channel looking up-bay at the three center stations of Figure P2. As can be seen the structure is quite complex showing four distinct regions of velocity separated by two divergences and a frontal convergence. This structure appears to be repeatable and, therefore, predictable.

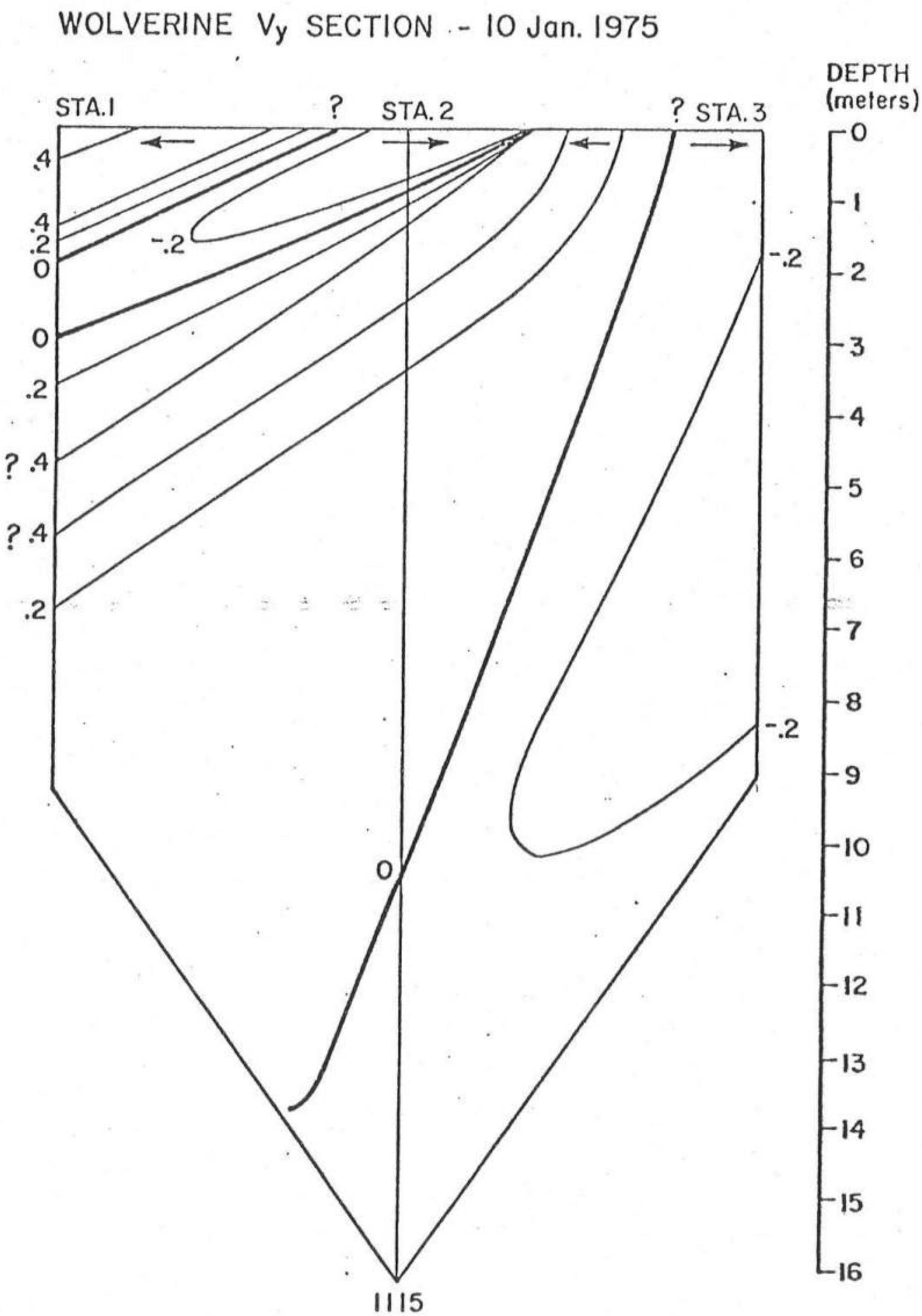
In summary, we believe that further field work will allow us to reduce the uncertainty of the currents in both time and space. Thus the errors from this source in oil spill position would be reduced from a few miles to a few tenths of a mile.

Winds

A comparison of wind observations at Dover and at Brandywine by octant was undertaken. A direct correlation of hourly observations from the two locations showed a correlation coefficient of less than 0.6 in all octants. Thus wind observations at Dover are a very poor indicator of conditions over the Bay.

In an effort to improve on this, correlations were run on time-logged three-hour running averages for each octant. Logs up to plus or minus twelve hours were calculated. Fitting coefficients were chosen for the log time giving the best fix. The results show an improvement over the direct correlation of hourly data in every octant with optimal correlation coefficients ranging from 0.38 to 0.89 depending on the octant.

FIGURE P3



Structure of the Cross-Channel Component of Velocity

Further wind observations in the Bay would allow the validity of the predicting equations to be checked and extended to other seasons of the year. Correlation with observations at additional land stations might substantially increase the worst correlation coefficients.

Further wind observations in the day could allow the modified the predicting equations to be checked and extended to other seasons of the year. Correlations with a second site or additional wind stations might substantially increase the multiple correlation coefficients.

COMPUTER MODELING OF OIL DRIFT AND SPREADING IN DELAWARE BAY

by Hsiang Wang, John R. Campbell, and John D. Ditmars

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