let subsequent programs produce plots like figure 3. Land segments are stored somewhat differently from overall targets and are processed by programs DIGICOPY and SEGMATRX rather than OBJECTS and DIGIPRES.

OBJECTS performs several functions. The sequence of points representing a target outline on the digitizer table is scaled, rotated, and projected into the final coordinate system. The grid cells occupied by these points are noted, and the grid outline of the target is completely connected using subroutines GETLIM, NBR, and TRACK. The grid cells inside the outline are then found using subroutine FILL. Grid locations of the targets, or segments, are compactly stored in arrays using the compaction methods described previously. The arrays are then stored on a direct access disk in such a way that they are accessible to the trajectory program SPILL via subroutine NEWBLK's paging system. They are also accessed by program OBJPLOT, to produce drawings of the target locations, as in figures 1 and 2. SEGMATRX performs an identical function for land segments.

PAGING SYSTEM FOR LARGE ARRAYS

The 480 × 480 arrays identifying targets and land segments occupy almost 1.4 megabytes of storage. Since only a small portion of each array is needed at any time, a paging system has proven economical in reducing computer core requirements.

Each large array is dividied into 30 × 30 blocks, which are stored as direct-access records on a disk. The paging system will retain the most recently used blocks in core, and access the others as needed. A further refinement for the array of targets is to construct a 16 × 16 array (one element for each block of the target array) that indicates presence or absence of target categories in each of the blocks. Thus, by checking the smaller array, the computer can determine whether or not it is necessary to read a block of the larger array.

WINDS

The subsections which follow explain how wind data is put into a form that can be used for oilspill simulation. Movement of oil under the influence of wind is covered in "Oilspill Trajectory Simulation."

STOCHASTIC MODEL OF WIND DATA

The variation in the wind is represented as a first-order Markov process. That is, the wind in one time-step is a random function of the wind in the previous time-step. This reflects one's experience that if the wind is presently out of the north at 5 knots, the wind 3 hours or so from now will quite likely be the same, though there is a smaller chance of a large wind shift. A probability transition matrix, constructed from the historic wind record is used to model this Markov process. An example of a wind transition matrix is shown in figure 4, and provides for 41 wind velocity states (8 directions time 5 speed classes, plus the calm state). The elements of this matrix are the probabilities that a particular wind velocity will be succeeded by another wind velocity in the next time step. For example, if the wind is now from the north at 10 knots, row 2 of the matrix shows there is a 22 percent chance that, 3 hours from now, the wind will still be from the north at 10 knots, and that there is a 9 percent chance it will be from the northwest at 5 knots. If the present state of the wind is i, then the next wind state, j, can be randomly chosen by procedures described in the subsection, "Constructing Wind Transition Matrices: Programs RAWWIND, LISTWIND, and WINDTRAN."

Program WINDTRAN constructs the wind transition matrix from the historic record at a wind station. The resulting matrix is a description of the frequencies of wind velocity transitions that have occurred during the period of record. Probabilities of transitions not occurring in the record are assigned the value of zero.

There is an important difference between sampling winds from a Markov transition matrix constructed in this manner, and simply reading the historic wind record with randomly selected starting days. Although neither technique will model an individual transition which has not occurred in the past, the Markov process model can yield sequences of transitions which have not been observed in the historic record. Since a 30-day oilspill trajectory, with winds sampled every 3 hours, will involve a sequence of 240 wind transitions, a far greater number of sequences can be sampled from the transition matrix without repetition than is available from reading the historic record. In effect the difference is that reading solely from the historic record assumes that only wind transition sequences that have occurred in the past can happen in the future, whereas sampling from a transition matrix assumes that the sequence of wind transitions observed in the historic record is only a sampling of some underlying distribution. Considering that usually only 5 to 10 years of historic record is available, and that the oilspill simulation is to represent an exploration and production period of 20 to 25 years, this assumption seems appropriate.

The ideal wind data would be obtained from long-term weather stations located in the area of interest measuring wind velocity at the surface of the ocean. Unfortunately, there are few permanent stations at

NEXT WIND IS OUT OF ... AT SPEED ... IN PERCENT.

LAST FROM DIR	SPD	CALM	N					NE					E					SE					S					SW					W					NW				
			5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25	5	10	15	20	25
CALM	0	27	2	1	0	0	0	3	0	0	0	0	34	3	0	0	0	4	0	0	0	0	1	0	0	0	0	1	0	0	0	0	6	4	1	0	0	7	3	1	0	0
N	5	28	10	13	1	0	0	6	1	0	0	0	11	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	12	11	4	0	0
N	10	10	15	22	6	0	0	9	1	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	3	0	0	4	12	7	1	0
N	15	6	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	6	0	0	11	11	44	6	0
N	20	50	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NE	5	26	6	1	0	0	0	9	1	0	0	0	16	4	0	0	0	8	1	0	0	0	0	0	0	0	0	1	0	0	0	0	8	4	1	0	0	3	5	6	0	0
NE	10	22	0	22	0	0	0	0	0	0	0	0	0	11	0	0	0	0	11	0	0	0	0	11	0	0	0	0	0	0	0	0	11	0	0	0	0	11	0	0	0	0
NE	15	0	0	**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NE	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NE	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	5	11	1	0	0	0	0	1	0	0	0	0	50	11	0	0	0	4	1	0	0	0	0	1	0	0	0	1	0	0	0	0	8	5	0	0	0	2	2	0	0	0
E	10	7	0	0	0	0	0	2	0	0	0	0	40	27	4	0	0	5	2	1	0	0	1	0	0	0	0	0	0	0	0	0	4	2	0	0	0	2	1	0	0	0
E	15	0	0	0	0	0	0	0	4	0	0	0	4	28	24	0	0	0	4	16	12	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
E	20	0	0	0	0	0	0	0	0	0	0	0	0	13	25	0	13	0	0	13	25	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	25	0	0	0	0	0	0	0	0	0	0	0	0	0	33	33	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SE	5	13	3	0	0	0	0	2	0	0	0	0	46	6	1	0	0	10	4	1	0	0	1	2	0	0	0	1	0	0	0	0	4	1	0	0	0	4	2	1	0	0
SE	10	2	0	0	0	0	0	0	0	0	0	0	9	7	2	0	0	11	20	18	7	2	4	2	4	0	0	2	2	0	2	0	2	0	2	0	0	0	0	0	0	0
SE	15	0	0	0	0	0	0	3	0	0	0	0	10	3	8	8	0	0	10	26	18	3	0	3	8	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
SE	20	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	4	0	8	19	23	8	0	0	4	12	0	0	0	0	4	0	0	0	0	4	0	0	0	0	0	0
SE	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	29	29	14	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	5	26	3	0	0	0	0	3	0	0	0	0	24	0	0	0	0	3	0	3	0	0	15	6	0	3	0	9	6	0	0	0	0	0	0	0	0	0	0	0	0	0
S	10	9	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	9	3	3	0	0	12	12	12	3	0	9	9	3	0	0	6	9	0	0	0	0	0	0	0	0
S	15	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	6	6	0	0	0	6	19	19	0	0	0	13	13	6	0	0	0	6	0	0	0	0	0	0	0
S	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	29	0	0	0	0	29	0	0	0	0	0	0	0	14	14	0	0	0	0	0	0	0
S	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SW	5	27	0	2	0	0	0	5	0	0	0	0	15	0	0	0	0	6	0	0	0	0	2	5	3	0	0	8	5	0	0	0	8	6	0	0	0	5	3	0	0	0
SW	10	20	3	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	7	7	0	0	0	23	7	0	0	0	3	13	0	0	0	3	0	3	0	0
SW	15	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	13	0	0	0	0	13	0	0	0	0	0	25	13	0	0	13	13	0	0	0	0	0	0	0	0
SW	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0	0	0	0	33	0	0	0	33	0	0	0	0	0	0	0	0
SW	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W	5	33	1	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	0	0	0	1	0	0	0	0	2	1	0	0	0	23	7	1	0	0	10	7	2	1	0
W	10	15	0	1	1	0	0	1	0	0	0	0	3	0	0	0	0	1	0	0	0	0	1	0	0	0	0	3	1	1	0	0	25	17	2	2	0	15	13	3	1	0
W	15	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	13	8	3	0	11	29	21	11	0
W	20	7	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	7	7	7	7	21	14	0
W	25	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0
NW	5	27	6	1	1	0	0	2	0	0	0	0	10	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	8	4	1	0	0	19	14	4	1	0
NW	10	7	4	2	1	0	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	7	4	1	0	0	20	30	15	2	0
NW	15	2	5	2	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	11	29	31	10	0
NW	20	0	7	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	0	2	13	38	26	3
NW	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	25	50
OVERALL		16	2	2	0	0	0	2	0	0	0	0	24	5	1	0	0	3	1	1	1	0	1	1	0	0	0	1	1	0	0	0	8	5	1	0	0	8	8	5	1	0

* Indicates greater than 99 percent probability

FIGURE 4.—An example of a wind transition matrix. A 3-hour wind transition matrix for winter at Point Arguello, California (See also fig. 5).

sea—a handful of lightships and "Texas towers." Thus, it is necessary to find other sources of data that can reasonably portray winds at sea.

Wind data recorded by ships have the advantage of originating from the area of interest and of (usually) being measured near the sea surface. For determining average wind conditions, these data are quite useful, although they may reflect the tendency of ships to avoid adverse weather. However, because the data are not collected on a consistent, regular basis, they are not suitable for calculating wind transition probabilities.

Permanent weather stations provide long-term, continuous records of winds. It is not difficult to find stations that sample wind velocity every three hours and have been in operation for over five years. Such data are needed for constructing wind-transition matrices. However, permanent weather stations are usually located onshore (often at airports), away from the areas of oilspill interest, and may also be influenced by topographic effects, such as mountains.

The model combines the advantages of both types of data by comparing averaged ships' data, such as wind roses, for different parts of the study area, with the same data for permanent weather stations. In this manner, each part of the study area can be associated with the permanent weather station that most closely matches the ships' data in that region. Although this does not necessarily mean that the wind transition data are exactly the same, it appears to be the best that can be done with the available data.

CONSTRUCTING WIND TRANSITION MATRICES: PROGRAM RAWWIND, LISTWIND, AND WINDTRAN

Data collected by permanent weather stations are available on magnetic tapes in standardized formats. Program RAWWIND reads these tapes, excludes extraneous data, and stores the wind record for each day on a disk file in a compact, unformatted form. Once processed onto the disk file there is no further need for the rather cumbersome weather station tapes.

Wind sampling procedures may differ among weather stations. For example, some collect data at hourly intervals, others at six-hour intervals; some only collect data in the daytime. To ensure that the weather station record is suitable for sampling wind transitions, program LISTWIND provides a compact printout of the wind data. By examining this printout, the analyst can decide upon the appropriate course for further wind data analysis.

Once the wind data for a station are stored on a disk file in suitable form, a wind transition probability matrix is constructed for each season by program WINDTRAN. This program reads the wind record at a specified sampling interval, and classifies the wind into one of 41 wind velocity classes (eight directions times five speeds, plus the calm). It then looks ahead to the next sample to determine how the wind has changed. When data input is completed, WINDTRAN computes a wind transition probability matrix, with elements, $a_{i,j}$ as follows:

$$a_{i,j} = \begin{cases} \dfrac{n_{i,j} \times 10{,}000}{\sum\limits_{k=1}^{41} n_{i,k}}, & \text{if } \sum\limits_{k=1}^{41} n_{i,k} > 0 \\ 0, & \text{if } \sum\limits_{k=1}^{41} n_{i,k} = 0, \end{cases} \qquad (1)$$

where

$a_{i,j}$ = probability (times 10,000) that, if the wind is in state i, the next sample will be in state j,

$n_{i,j}$ = observed number of transitions observed from state i to state j.

Thus, if R is a random number between 1 and 10,000, and, the starting state is i, the next state, k, can be found by summing the elements of row i such that:

$$\sum_{j=1}^{k+1} a_{i,j} \geqslant R > \sum_{j=1}^{k} a_{i,j} \qquad (2)$$

WINDTRAN must perform several other operations, in addition to constructing the transition matrices. First, it calculates an average speed and direction for all of the observations within each velocity class. This is done because selection of the classes is somewhat arbitrary, and given a finite number of samples, could introduce a bias in the simulated wind record. By using actual averages for each class (rather than only the nominal speed and direction), a simulated wind record should, in the long run, reproduce the averages of the observed winds. Thus the nominal designation of a class as "from the north at 5 knots" may actually mean "from the direction 2 degrees at 5.3 knots." Of course, as the number of observations increases, the two will become more and more alike.

The assumed wind drift angle (usually 20 degrees clockwise, in the northern hemisphere) is added directly to the average direction determined for each category. Then, the average wind vector is divided into x and y components of the coordinate system. Thus, the velocity class is found by a random sampling of the wind transition probability matrix, and the wind vectors for computing oilspill movement are found in a table for the appropriate class.

The final operation of WINDTRAN is performed to enhance the computational speed of later programs. Equation 2, which uses the ordinary transition matrix, is unnecessarily cumbersome for fast calculations: one must try an average of 20 values of k for each solution. Greater speed is attained by sorting and summing across the rows so that, in effect, the most likely transitions are sampled first. An additional matrix is needed as an index to the sorting, but since most wind transition probability matrices are strongly diagonal, the net result allows a much faster search.

The sorted wind transition probability matrices, along with the corresponding indices, and the x and y oilspill movement vectors, are all stored on a disk file.

DEFINING WIND ZONES: PROGRAM WINDZONE

As explained earlier, winds in different parts of the study area may be simulated using the records of different permanent weather stations. Program WIND-

ZONE assigns to each 10×10 block of grid cells a selected wind station number. By reading the wind station number, program SPILL can find the correct wind station to use for any location. Up to six sets of wind transition probability matrices, constructed from the records of six permanent weather stations, are permitted. Figure 5 shows an example of wind zones used for OCS Lease Sale 48; this particular analysis used four weather stations.

CURRENTS

Ocean currents are represented in the model as varying from month to month in a deterministic fashion. This is in contrast to the winds, which vary randomly over a relatively short time period. Spatial variation of currents is incorporated by dividing the study area into as many as 600 subareas, and assigning monthly current vectors to each of these subareas.

The model does not actually model ocean currents but utilizes a current field determined by other means. Input data for currents, whether derived from mathematical models or from direct measurements, must conform to the assumption (made in the preceding sections) that winds and currents are uncorrelated within a given month. Therefore, the current field used for the model is the baroclinic current, and all wind-induced currents must be represented with the wind data.

Tidal currents are also not included in the model. Generally, the waters in which tides are an important transport mechanism are not within the model's intended scope of analysis.

CURRENT DATA ENTRY AND STORAGE: PROGRAMS CURPOLY AND CURMATRX

Current data are made available to the model from maps of the study area showing the current field for each month. The study area is then divided into subareas or polygons, with 600 the maximum number. Each polygon is assigned a current vector for every month. The polygons are, therefore, a finite-element representation of the current field.

The polygon configuration must be able to adequately characterize the overall monthly current fields with the fewest possible polygons. At present, the judgments of the analysts and modelers are the sole determinants of the polygon configuration for each analysis. No mechanical polygon construction routine exists. Figure 6 shows a monthly current field of 518 current vectors used by the model in a run for a southern California risk analysis (see Slack, Wyant, and Lanfear, 1978); figure 7 shows the 518 polygons.

The vertices of the current polygons are first digitized in the same manner as land segment polygons (see "Land and Targets"). Program DIGICOPY transfers the digitized information into direct access disk datasets. Program CURPOLY combines the information in these datasets into a single current polygon file. Program CURMATRX then carries out the final processing steps to make current data accessible to program SPILL: (1) The polygon vertices are scaled, rotated, and projected from digitizer table coordinates to the final model coordinate system; (2) a 480×480 2-byte integer array is filled with the current polygon identification numbers corresponding to each grid cell; (3) this array is stored on a disk file accessible to program SPILL's paging system; (4) the monthly current velocities associated with each polygon are read from cards and stored in another disk file. CURMATRX also generates diagnostic plots for data checking and a printout of the grid system showing the current polygon associated with each cell.

CURRENT DATA CHECKING

The special requirements of the model and the occasional need to obtain current data from several sources necessitate the translation of large amounts of current data to the appropriate format at the beginning of every analysis. Several programs of the model enable quick and thorough graphical checking of the final-format current data to detect translation errors. Graphics are especially effective in detecting major errors. Programs CURPLOT and CURMATRX provide plots of polygon locations, plots of spatial current fields, by month, and diagnostic printouts of the final 480×480 current grid.

OILSPILL TRAJECTORY SIMULATION

MONTE CARLO SIMULATIONS OF OILSPILL TRAJECTORIES

For each selected launch point, a large number of hypothetical oilspills are released at randomly chosen days within the year and are moved about by randomly sampled winds and currents. With sufficient trials, the statistical behavior of the trial spills will approximate the statistical behavior of spills integrated over all possible combinations of release times, winds, and currents.

The model analyzes oilspill trajectories from a set of potential launch points which are chosen to represent different proposed oil production sites in the OCS lease area and proposed transportation routes. A total of 100 launch points may be selected. From each launch point, 500 hypothetical oilspills are simulated for each season of the year, resulting in as many as 200,000 simulated oilspills for a model run. The next section shows how these simulation results are further analyzed to determine risks from various parts of the lease area.

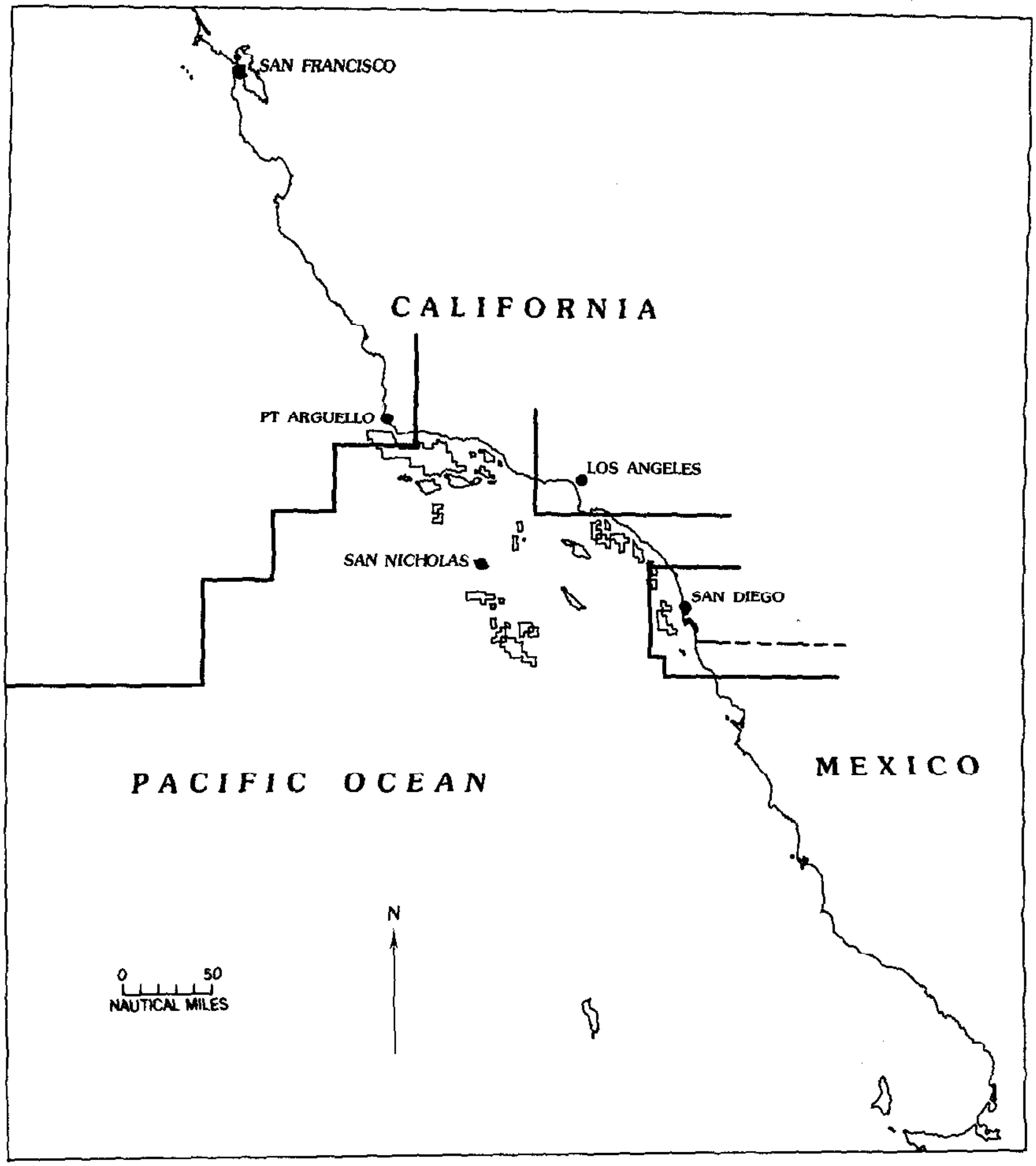

FIGURE 5.—Wind zones used for OCS Lease Sale 48—southern California. Four weather stations were used instead of six. Rectangles are proposed lease tracts (Slack, Wyant, and Lanfear, 1978).

A single launch point may adequately portray a group of proposed lease tracts, but additional points are often needed to represent pipelines and tanker routes. An option of the model allows a launch point to be specified as a straight line, rather than a single point; the 500 spills per season are started from 100 uniformly spaced locations along the line, 5 spills at each location.

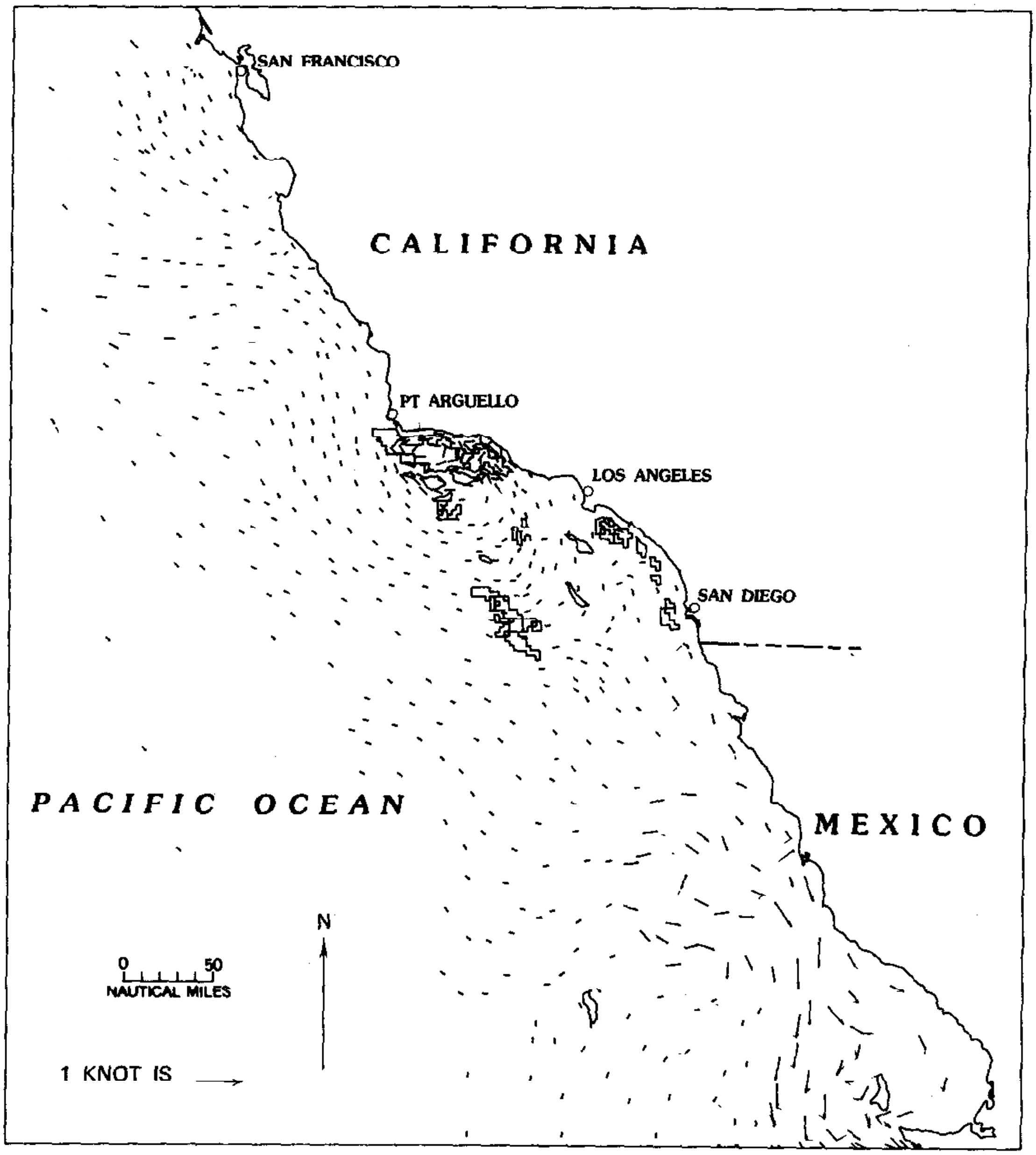

FIGURE 6.—Monthly current field for southern California (March). Rectangles are proposed lease tracts. Lines represent current vectors (Slack, Wyant, and Lanfear, 1978).

EFFECTS OF WIND AND CURRENT ON OILSPILL MOVEMENT

The effects of wind on a parcel of oil flowing on the sea surface have been studied by a number of investigators (Murray and others, 1970; Murty and Khandekar, 1973; Allen and Thanarajah, 1977; Phillips and Groseva, 1977; Stolzenbach and others, 1977; Zilitinkevich, 1978). There appears to be only partial agreement on the general theory of wind-induced oilspill movement, probably because of the complexity of the subject. Winds may transport oilspills through wind-generated currents, wind-induced waves, and by

FIGURE 7.—Current polygons for southern California developed from the monthly current field. Rectangles not containing a vector are proposed lease tracts (Slack, Wyant, and Lanfear, 1978).

direct wind shear; these effects can combine in different ways, depending on characteristics of the oil, sea conditions, and ocean-bottom topography.

Despite the theoretical difficulties, an empirical approach to predicting oilspill movement has proved quite successful in practical trajectory modeling. First described by Smith (1968) in a study of the Torrey Canyon spill off the coast of Great Britain, the method requires the following simple assumptions:

- The effects of wind and current on the oilspill act independently, and can thus be described as a simple vector sum of velocities.
- The wind vector is a constant small fraction of the wind speed, but the direction of oilspill mo-

tion induced by the wind is at a nonzero angle to the direction of the wind due to Coriolis forces.

- The current vector is equal to the current velocity.

Regarding the second assumption, the wind vector has been estimated empirically to equal 3.5 percent of the wind speed with a drift angle of 20 degrees to the right (clockwise) of the wind direction for the northern hemisphere (Smith, 1968; Stolzenbach and others, 1977).

The independence of the effects of wind and current allows the forces to be calculated separately and the resultant motion of the oil to be taken as the vector sum. This requires, of course, that the current field be free of wind effects. Data on currents for past trajectory analyses using the model have come from many sources. Results of drift studies and the output of computer models have been used. Precise assessments of the validity of either drift study results or mathematical model outputs are hard to come by, but something can usually be said about the sensitivity of a set of oilspill risk analysis model results to assumptions regarding currents. More exactly, it is important throughout an analysis to remain aware of whether oilspill movement would be current-dominated or wind-dominated. Often, dominance differs both seasonally and spatially.

Figure 8 contrasts spill movements dominated by each mechanism. The figure shows 10 simulated trajectories launched from a point in a proposed oil production area off the Mid-Atlantic coast (see Slack and Wyant, 1978). For this area as a whole, average wind speed is 12.3 knots (based on lightship data). Assuming winds move oilspills at about 3.5 percent of the winds' own velocities, the winds in this area would, on the average, induce a 0.43 knot speed in spill movements. The currents in the immediate vicinity of the proposed production area are weak—0.1 to 0.3 knots—and the meanderings in simulated trajectories induced by shifts in the winds can be readily seen in the figure. The Gulf Stream runs to the east of the proposed production area, with currents at 1.0-2.0 knots. As simulated spills leave the lease area to the east, currents dominate over winds in influencing movement. Thus, the simulated spills in the eastern portion of the area move rapidly eastward into the Atlantic Ocean, with little meandering.

OILSPILL MOVEMENT

Program SPILL simulates oilspill movement as a series of displacements over finite time-intervals. For each time step in the duration of a hypothetical spill, two vectors—one representing the effect of the wind and the other that of the current—are summed to obtain the displacement of the spill's center of mass. The spill is then moved in a straight line between its old and new grid coordinates as illustrated in figure 9, and any cells through which the spill passes are checked for the presence of targets. The tracking of a hypothetical spill continues in this manner until a time limit (usually 30 or 60 days) is exceeded, or until the spill contacts land or leaves the area being modeled.

The choice of the time step is based on the sizes of the current polygons, the persistence of the wind data, and practical limits for computer run time. Since a current vector is selected only at the beginning of a time step, a time step short enough to consider the smaller current polygons must be chosen, or they will be skipped over and ignored. Assuming a spill movement speed of 0.5 to 1.0 m/s, a 3-hour time step usually fulfills this condition; where current polygons are larger, a 6-hour time step may be satisfactory. A 3- to 6-hour time step also appears to adequately characterize the wind data in that it makes the model sensitive to the variability in synoptic weather patterns. Finally, a 3-hour time step is a realistic limitation considering the computational speed of program SPILL using existing Geological Survey computer facilities.

Although program SPILL's function—moving a simulated oilspill through cells, checking each cell for targets, and counting hits on the targets—is simple in concept, it is a tedious and time-consuming task. A detailed explanation of how program SPILL accomplishes this, using a variety of programming techniques to increase its running speed, is not included in this paper. To understand the probability calculations, however, it is important to know the rules used for recording contacts (hits) of simulated oilspills with the targets. These rules apply to each simulated oil spill:

- The spill may only be designated as hitting or missing each of the 31 target classes; multiple hits on the same target class count as only one hit.
- SPILL automatically determines which months a target is vulnerable to oilspill damage, and counts hits only during these months.
- Upon first contact of the spill with each target class, the simulated age of the spill is recorded.
- If a spill contacts a cell containing land, its simulation is terminated, and the land segment code of that cell is noted; thus the spill may hit no more than one land segment in each set of land segments.
- If the spill moves off of the grid, its simulation is terminated and the direction in which it left the grid is recorded.

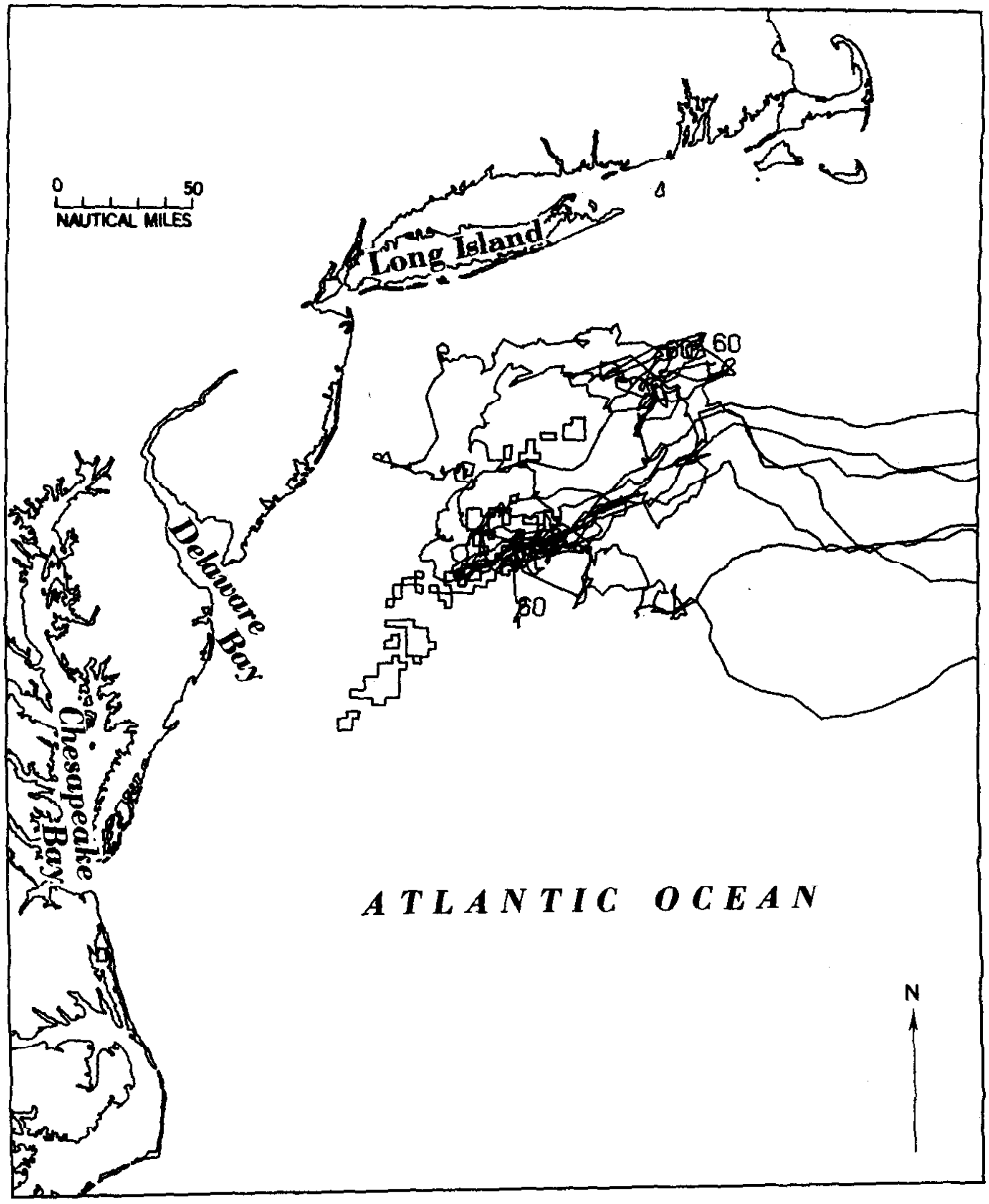

FIGURE 8.—Example oilspill trajectories for a spill site (P4) near the center of the proposed Mid-Atlantic (OCS Lease Sale 49) lease area; summer conditions. Number on trajectory is the time to the end point in days. (Slack and Wyant, 1978.)

- If a spill continues beyond a fixed time limit (usually 30 or 60 days), it is assumed to have decayed, and its simulation is terminated.
- The final grid location of the spill is recorded.

Program SPILL produces a record, on a disk file, of the behavior of each hypothetical spill. A summary of SPILL's output is created by program SUMMARY, which shows the results in groups of 100 spills, so that the variability of the Monte Carlo simulation can be checked.

A variation of SPILL (identical to the main program, but containing plotting subroutines) is used to produce graphical displays of trajectory runs. Graphical displays help the analyst ensure that simulated spills behave in a logical manner, and effectively detect errors such as improper scaling factors and reversed wind or current fields. These displays, such as those shown in figures 8 and 10 are also useful as examples of the performance of the model. Conclusions about oilspill behavior from such displays should be cautioned against, since a figure showing 10 spills represents only 0.5 percent of the 2000 spills launched. While average probabilities of hits by oilspills is a meaningful concept, there is no such thing as an "average" trajectory.

A paging system for storing and retrieving the large matrices containing current and land segment data holds down the size of SPILL. Even so, its 500-kilobyte size makes it the second largest of the model's programs. For a large OCS lease sale analysis, SPILL may require more computer operating time than all of the model's other programs combined. Because of its long running time, SPILL is usually run in 5 to 20 independent jobs, so that no one job uses more than one-half hour of central processing unit (CPU) time. The output files of all the jobs are concatenated to form the complete output file. On an IBM 370/155 computer, SPILL can operate at a speed of 1 millisecond per time step, or about ¼ second for a single 30-day oilspill simulation.

RISK CALCULATION

CONDITIONAL PROBABILITIES

Program SPILL records, on a disk file, data about the trajectories of 2,000 hypothetical oilspills from each launch point and the contacts made by these trajectories on targets and land segments. SPILL does not perform any analysis or interpretation of this data; summations and statistical analyses are performed by a subsequent set of programs. These programs determine the likelihood, or conditional probability, that certain events, such as contact with targets or land segments, will occur if an oilspill occurs at a given launch point.

Separating the conditional probability analysis from the Monte Carlo simulation permits the large and time-consuming program SPILL to remain relatively straightforward, while its output can be tailored to user requirements with small, easily modified programs. Two programs, HITPROB and LANDSEG, are used to calculate the conditional probabilities of spills contacting targets and land segments, respectively. A third program, FIRSTPAS, analyzes the travel times oilspills need to reach targets. All three programs operate in a similar manner, scanning the disk output of SPILL to review the results of each trajectory run, and selecting and tabulating the necessary information.

CONDITIONAL PROBABILITIES OF CONTACTING TARGETS: PROGRAM HITPROB

Program HITPROB calculates the probability that, if an oilspill occurs at a given launch point, it will, within a specified period of time, contact a target. Conditional probabilities are calculated for each launch point for oilspills with maximum ages of 3, 10, 30, and 60 days. Typical output from HITPROB is shown in table 3; this same information is stored on a disk for use by program NU, which calculates overall risks. (See section on "Probability that an Oilspill will Occur and Contact a Target," for elaboration of program NU). Since SPILL records a target as "hit" only if contact occurs during a month in which it is vulnerable to oilspill damage, the condition probabilities automatically reflect any seasonal vulnerability.

It is important to recognize that the conditional probabilities calculated by program HITPROB refer to each target as a whole and imply nothing about the distribution of risk among any subdivision of that target. For example, the target "sandy beaches" may extend for several hundred miles of coastline, and risks to particular beaches may differ. Program HITPROB would only calculate the conditional probability that an oilspill originating at a given point would land on a sandy beach somewhere in the study area; it would tell nothing about the likelihood of contacting a specific beach (except that it is less than or equal to that of contacting "sandy beaches"). If such differentation is desired, then each item should be defined as a single target or the land segment feature of the model should be used.