1-1-1979

A fishery- oil spill interaction model.

M. Reed

M. L. Spaulding
University of Rhode Island

Citation/Publisher Attribution
Reed, M., and M. L. Spaulding. "A fishery- oil spill interaction model.." *Proc. 1979 oil spill conference (prevention, behavior, control, cleanup), Los Angeles, Ca., March 1979, (American Petroleum Institute, Washington DC, Publication 4308)* (1979): 63-73. doi: 10.7901/2169-3358-1979-1-63.

A fishery- oil spill interaction model.

A FISHERY-OIL SPILL INTERACTION MODEL

Mark Reed and Malcolm L. Spaulding
Department of Ocean Engineering
University of Rhode Island
Kingston, Rhode Island 02881

ABSTRACT: *An oil spill behavior and fates model (see paper by P. C. Cornillon* et al. *elsewhere in this volume) has been coupled to a fisheries model*[54] *to produce dynamic simulations of the interactive effects between an oil spill and the cod fishery on Georges Bank, with impacts being projected into the commercial catch. Four trial cases are documented: spills occurring in December and April, with and without chemical treatment. Several systems problems are discussed, along with present and anticipated efforts to bring the set of models from its current preliminary state to one in which useful inferences may be drawn.*

Due to increasing rates of both oil transportation through our coastal waters, and hydrocarbon exploration on our continental shelves, a large number of environmentally significant decisions are being and will continue to be made, in which marine-related risks, costs, and benefits are weighed and traded off against each other. This model is one result of a larger interdisciplinary effort at the University of Rhode Island comparing environmental effects of treated and untreated oil spills, which attempts to shed some light on these tradeoffs, and thus facilitate decision-making processes among concerned governmental agencies.

Model description

To what extent oil spills at sea affect the commercial fish catch over the ensuing years is the specific problem addressed in this paper. We have attempted to estimate only first order, direct effects—those that are assumed to occur through egg and larval mortality, an assumption upon which many marine biologists concur.[15,42,74] The biological impacts model formulated here, therefore, contains as subcomponents a population model of the fish stock, a model to simulate advection and diffusion of larvae, and an oil behavior and fates model. The interaction of these submodels for a complete impact estimate is outlined schematically in Figure 1.

Since this particular environmental problem is merely one of a much larger set, many elements of which are amenable to this type of explicit simulation technique, system development has been along modular lines. Possible future applications include, for example, power plant entrainment and municipal sewage outfall impacts. Ultimate model evolution is aimed at a broader holistic concept, including a species-specific ecosystem model to facilitate food web pollutant concentration studies, a numerical hydrodynamic-mass transport model, and a variety of impact sources and mechanisms operating alone or in concert.

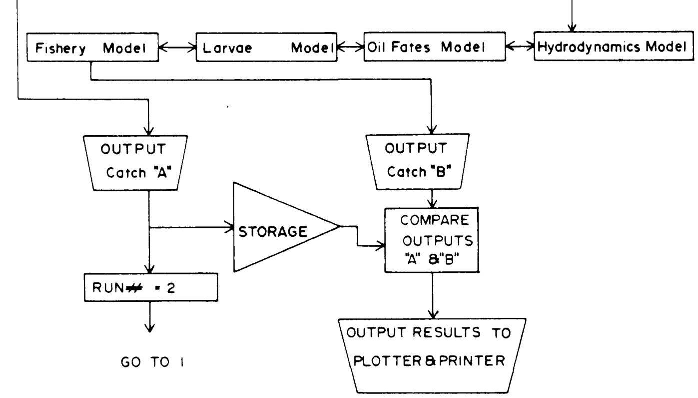


Figure 1. Overview of the model system

The fishery model. The Georges Bank cod *(Gadus morhua)* stock has been selected for the initial application of the model for several reasons. The Atlantic cod is one of the most important species in the New England area, from both the standpoints of economics and of biomass landed. In 1976, for example, Georges Bank accounted for approximately 95 percent of the 56 million pounds of cod landed by the United States commercial fleet. This was about 11 percent of the total New England commercial landings, and was valued at about $16 million at ex-vessel prices.[45] Furthermore, the cod is biologically similar to other groundfish of the region in that it has pelagic eggs and fry susceptible to impact by oil spills. Such fish comprised over a third of the total weight of New England commercial landings in 1976, and accounted for a little less than a third of the total ex-vessel dollar valuation of the catch. To this extent, the impact on the cod fishery carries implications for the New England fishery as a whole.

Because of its importance throughout the North Atlantic, a great deal of research has been directed toward increasing our understanding of cod biology, so that the use of arbitrary parameters can be kept to a minimum. The presence of simpler fisheries models of this particular stock,[60,61,66] and more sophisticated models of other cod fisheries,[14,25,30] along with analyses resulting from National Marine Fisheries Service groundfish surveys[58,59] supply other valuable sources for comparison of methods and results.

The adult fishery model is constructed along well established lines,[2,6,7,66] whereas the egg and larval stages have been modeled using techniques drawn from other areas of mathematical ecology.[29,40,52,53,62,63] The structure of the fishery model is shown schematically in Figure 2.

The model has 18 age classes, enough to include all fish sampled in recent surveys.[31] They increase in length and weight according to a published growth equation[51] for the Georges Bank stock (Figure 3). The ith age-class is subject to a mortality equation following first order kinetics,

$$\frac{dN_i}{dt} = -(M_i + F_i)N_i \qquad (1)$$

in which M_i and F_i are natural and fishing mortality coefficients respectively, the former including all types not induced by the latter. Fishing mortality is assumed linearly proportional to standardized fishing effort

$$F_i = Q\,S_i\,E(t) \qquad (2)$$

Q is a species-dependent catchability coefficient; S_i is a net mesh selectivity for the ith age-class; and E(t) is a measure of the fishing effort exerted on the stock during the time interval t.

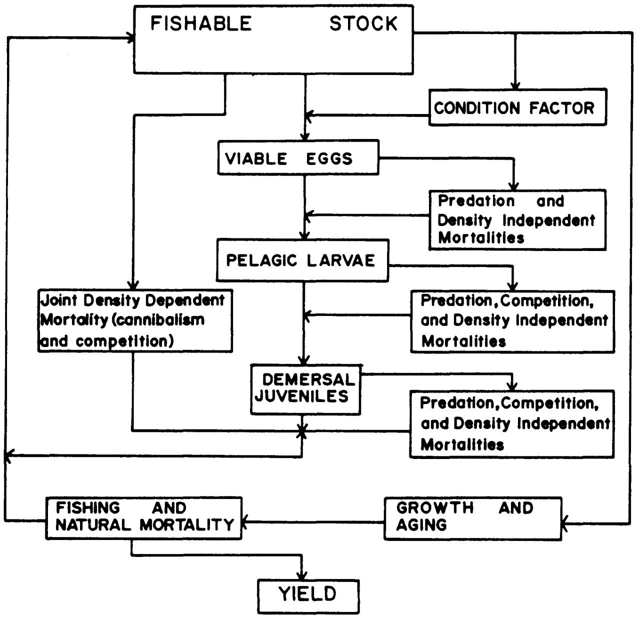


Figure 2. Schematic of the codfish population model

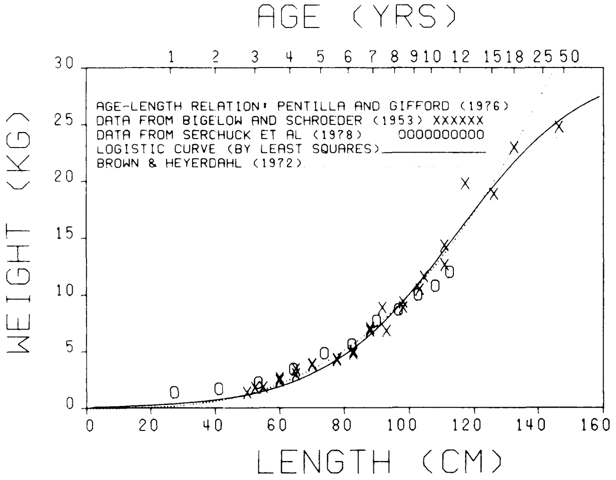


Figure 3. Growth curve for Georges Bank cod (the solid line is the curve used in the model)

The fecundity of cod appears well-correlated with weight, although, as with all such characteristics, the relationship varies from one stock to another.[8,21,26,27,49] This literature suggests a value of 200 to 250 eggs per gram female, which conforms reasonably well to an estimate by Bigelow and Schroeder[8] of one million eggs per average female, although falling somewhat short of their estimated maximum of 9 million.

The major uncertainties in the biological sector of the model exist in the egg and larval mortality representations. These are formulated to require as few arbitrary parameters as possible, while simulating these stages in sufficient theoretical detail to resolve toxic effects which vary in magnitude from one developmental stage to the next.

The equations governing egg (E), larval (L), and juvenile (J) mortalities are

$$dE/dt = (m_1 + m_2E)E \qquad (3)$$

$$dL/dt = (m_3 + m_4L)L \qquad (4)$$

$$dJ/dt = (m_5 + m_6J + m_7 \sum_{i=2}^{18} N_i P_i)J. \qquad (5)$$

Equations 3 and 4 each include density-independent (m_1, m_3) and density-dependent (m_2, m_4) mortality terms, whereas Equation 5 incorporates a set of adult-juvenile interaction terms (P_i) as well.

The theory upon which these equations are based derives from Lotka,[40] who employed the concept of a Taylor expansion about some hypothetical equilibrium value. In brief, density-dependent mortality of an intragroup nature, as associated with parameters m_2, m_4, and m_6, is intended to represent competition among individuals of the group for limited resources (*e.g.*, food). Density dependence between groups may result from competition for shared resources, or a parasitic relation. There is considerable evidence of cannibalism among Gadoids,[8,22] a fact which the third term in Equation 5 is designed to simulate. Further discussion of these equations, the theory behind them, and an algorithm for the numerical solution of Equation 5 may be found in Reed and Spaulding.[54]

Development of pre-recruits is modeled in 5 stages: eggs, yolk-sac larvae, larvae adapting to free-feeding, adapted free-feeders, and bottom-dwelling juveniles. These stages were selected as those between which definite differences in susceptibility to hydrocarbon toxicity can be observed.[37,38,67] Egg hatching rates are well represented by a negative exponential least-squares curve as shown in Figure 4. Yolk sac resorption requires from 4 to 12 days,[8,38,43,72] and for lack of any deterministic relation, eight days is used here. The larvae must then adapt to catching planktonic organisms, primarily copepod nauplii at this stage, and will die if not successful within four days. Dannevig[23]

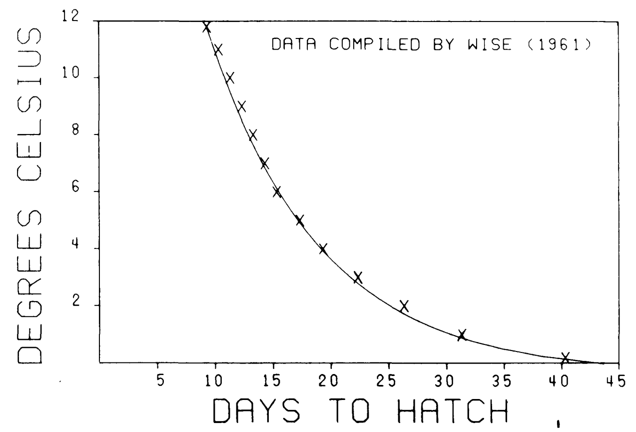


Figure 4. Hatching time as a function of temperature for cod eggs

found that about 70 days was required for cod larvae to achieve metamorphosis, and it is thought that they seek bottom about a month later. These development rates are certainly variable with such things as temperature and food availability, but except for hatching rates, constant values have been used in the model due to lack of hard data.

Temporal distribution of spawning on Georges Bank remains, in the words of Colton *et al.*,[18] something of an enigma, it being uncertain whether cod spawning activity is triggered by day length, temperature, or other environmental factors.[72] The issue is further clouded by indications that the population profile affects the time of peak spawning. Livingston (personal communication) has found this to be true for haddock, a closely related species, with older fish spawning earlier in the spring. Colton *et al.*,[16,17] and Walford,[65] support the observation that spawning occurs with varying degrees of intensity from November to late April, with a maximum occurring in March and a second smaller peak in the late fall. In light of this rather scanty information, spawning is modeled as occurring from November 1 to April 30, and is programmed as the step function shown in Figure 5.

Pre-recruit mortality parameters are notoriously difficult to evaluate, since what few values exist are usually derived from laboratory observations, which in general do not reflect conditions in the open ocean. It is nonetheless desirable to use whatever our best estimates may be, to reduce the need for blind "model tuning" in the final stages. Thus, a value equivalent to 60 percent mortality has been used for the density independent rate for eggs,[39] and it is hypothesized that juveniles die of natural causes (*e.g.*, disease or starvation) at about twice the rate of the adults.

The four remaining density-dependent parameters were assigned values resulting from a series of steepest descent optimization searches[66] using the sum of the squared differences between the modeled yield and the catch record from 1932 to 1952. Several approximately equivalent local minima were found, one of which was selected arbitrarily. This choice corresponds to the center curve of Figure 11. Further efforts in this area are discussed below.

The model was then verified by comparison with the entire catch record, 1932 to 1974 (Figure 6). Although the average error is on the order of 20 percent of the average catch, the model demonstrates a reasonable ability to follow the trends in the record (r = 0.81). The model tends, however, to overestimate the catch in years of low actual yield, and underestimate at the other end of the scale, as in the mid-1960's for example. This suggests that the model behaves more stably than the actual stock, a factor which must be considered in interpretation of results. It also reflects the importance of effects not included explicitly in the model, such as epidemic disease and climatic events, and belies any attempt to ascribe truly predictive capabilities to the model as presently formulated.

The ocean transport model. One of the major problems in the modeling of marine mass transport phenomena has been simulation of the complex processes involved in oceanic diffusion. That diffusion in the atmosphere is a non-linear (non-Fickian) phenomenon was demonstrated by Richardson[55] as the 4/3 power law. It has become apparent since that oceanic diffusivity also increases with the scale of diffusion, as reflected in the literature,[50,75] although the value of the exponent remains uncertain.

This non-linear behavior is explicable if we consider that turbulence on scales significantly larger than that being modeled will cause a net transport of a dispersing cloud, contributing to cloud growth only through shear effects. Small-scale effects such as molecular diffusivity will be relatively unimportant in most marine applications. Eddies with spatial scales of the same order of magnitude as that of the cloud itself will be most significant in cloud growth. As this growth occurs, the energy from larger and larger eddies becomes effective in the dispersion process.

At present, the model deals with the diffusion problem in the following manner. A theoretical relation between the variance(s) of a diffusing cloud and the diffusivity (D) is given by[20]

$$s^2 = 2Dt \qquad (6)$$

in which t is time. Let us assume a characteristic diffusion velocity (DUV) for the problem as a whole, the expected value E(DUV). It then can be shown that

$$E(DUV) = \sqrt{6D/dt} \qquad (7)$$

The value of D is then chosen from an oceanic diffusion diagram,[50] the diameter of the spawning area being used as the characteristic length. By superposition, the net transport of the k^th^ particle during the j^th^ timestep, dr_{jk}, is

$$dr_{jk} = (R_{jk}\, E(DUV) + U_{jk})dt \qquad (8)$$

in which U_{jk} is the net advective velocity contribution, and R_{jk} is a random variable chosen from a uniform distribution $[-1,1]$.

Advective transport phenomena in continental shelf regions are themselves responsible for a considerable amount of literature and research. Beardsley,[5] Bishop *et al.*,[9] Bretschneider,[10] Csanady,[19] Fischer,[24] and Nihoul[48] are a few recent examples. As in the case of diffusion, the preferred simulation technique involves the solution of the Navier-Stokes equations plus a conservation of mass equation on a phase space grid of sufficiently fine mesh to resolve the characteristics of interest. The available data for the verification of larval distributions hardly warrants the time and effort required to produce such a model.

At the other extreme, the arbitrary application of some approximate average southerly transport, such as the 15 cm/sec estimated by Bishop *et al.*,[9] for example, would result in model output of dubious significance. A temporary compromise solution was adopted utilizing drifter data compiled by Bumpus *et al.*[11,13] A triangular grid was constructed covering the area of interest (Figure 7), and seasonal velocity components were inferred at each node (Figures 8a-8d). Smooth transition from season to season has been achieved with a linear weighting scheme. Velocities within the grid are interpolated by fitting a plane through the values at the three nodes surrounding the point of interest and solving the planar equation for the value at the required location.

Preliminary verification of the spliced fishery-ocean transport model has been accomplished by comparison of predicted larval fish distributions with those reported by the National Marine Fisheries Service.[16] Figures 9a and 9b show perspective representations of two of these data sets. Although additional data is available for December

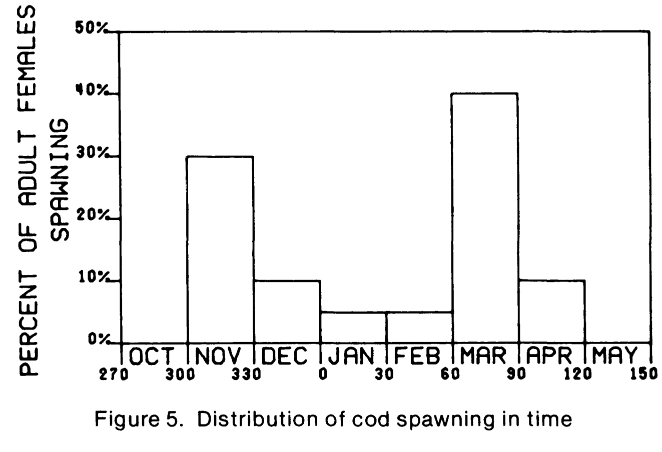


Figure 5. Distribution of cod spawning in time

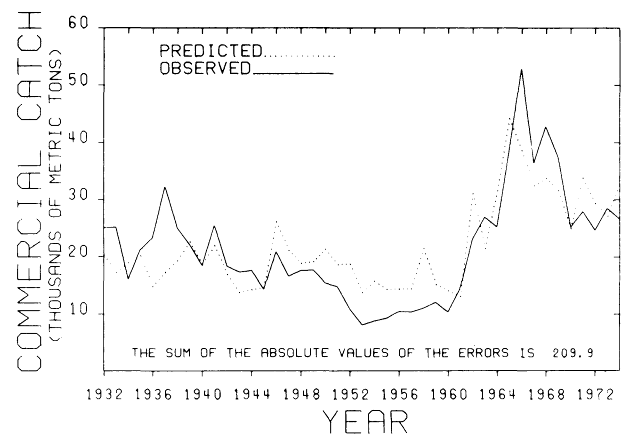


Figure 6. Comparison of modeled and observed catch for the years 1932-1974

and February, no direct comparison has been possible for the spring months. Such data is, of course, extremely expensive to accumulate. Hopefully, enough will become available in the near future to permit some statistical comparisons between the modeled distributions and those observed in the field.

For the present, qualitative comparisons have had to suffice (Figures 10a and 10b). That the magnitudes of the modeled distributions exceed those of the observed, indicates that dispersion and (or) prelarval mortalities exceed those being simulated. Since the population being modeled is smaller than that actually present, the (unknown) recreational catch being neglected in this analysis, peak larval concentrations as modeled should be less than those observed. Referring again to Figure 11, one could thus argue for use of mortality coefficients defined by the lower curve, since the central curve was used in obtaining Figure 9.

Case descriptions

Although the fishery and oil spill models have previously been run separately, this paper describes the first trial runs in concert. These trials were designed to demonstrate the basic capabilities of the system, as well as to reveal any unforeseen problem areas. In addition, some measure of pseudo "worst case" results was attempted. The following assumptions were made accordingly:

1. Uniform distribution of larvae in the top 10 meters
2. Location of eggs at the air-water interface
3. Spills occurring just after peak spawning periods, as shown in Figure 5
4. Spills occurring at the center of the spawning area (Figure 12)
5. Instant mortality upon entry into an area in which concentrations exceed 50 parts per billion (ppb)
6. Mortality of any eggs under surfaces covered by an oil slick

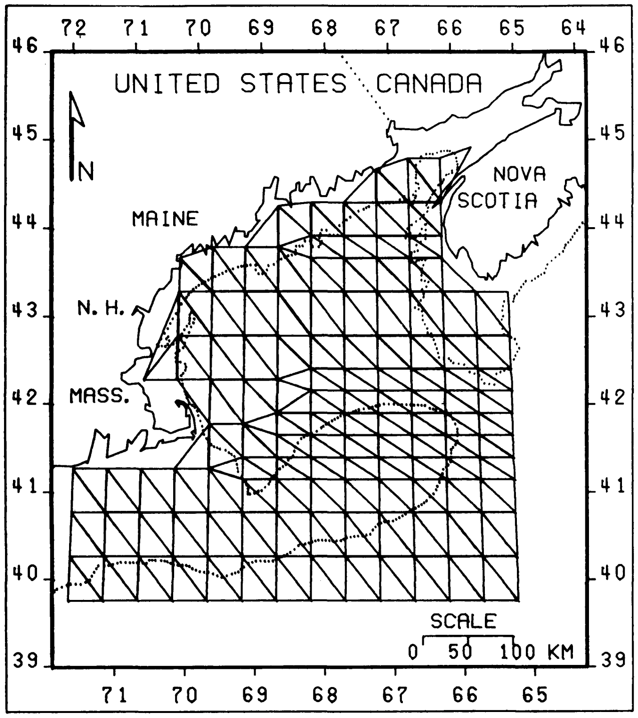


Figure 7. Map of the Georges Bank area, showing the 100-meter bathymetric contour, and the triangular elements used in the ocean transport model

The first two assumptions are simplifications incorporated in lieu of explicit modeling formulations in the vertical dimension. Larval distributions in the vertical may well be age-dependent,[33] although Miller *et al.*[41] found over 80 percent of larval haddock between 20 and 30 meters, which in this area approximately defines the depth limits of the thermocline. Distribution of eggs with depth, on the other hand, probably depends on the magnitude of vertical turbulence, since the eggs have only slight positive buoyancy, and vary in density according to the salinity of their environment.[72] The third and fourth assumptions are consistent with the attempt to have a strong impact on the population, while the fifth and sixth were made as conservative "zeroth" order approximations to facilitate interpretation of preliminary results.

Table 1. Characteristics of modeled cases, and related impact estimates[1]

Case number	Start of spill (Julian day)	Treated?	Mortality modes	Cumulative impact (metric tons)
1	December (350)	YES	1, 2, 3	0.48, 1.47, 0.29
2	December (350)	NO	2	1.30
3	April (90)	YES	2	0.96
4	April (90)	NO	2	0.64

1. Mortality mode numbers correspond to the curves in Figure 11.

Four distinct cases were run, the defining characteristics of each being shown in Table 1. The oil spill simulated had a volume of 10 million gallons, with release occurring over a 36-hour period. If chemical treatment effects were simulated, these began instantaneously over the entire area of the spill at hour 48. For each of the two seasons, wind effects were modeled from an actual time series. The wind was assumed to affect only that portion of the spill on the water surface, since the subsurface advective velocity fields already include average wind-driven components.

Although the model is designed with the capability to record and update toxicity measures such as exposure durations and peak concentrations encountered, oil-induced mortality has been assumed to occur whenever eggs or larvae enter an area in which concentrations exceed 50 ppb. This value is the present lower limit at which statistically significant results can be obtained from the oil behavior and fates model, and is somewhat higher than the 10 ppb level at which Kunhold[38] observed no noticeable effects.

Discussion of results

"Snapshots" of the progression of events following the spill are shown for cases 1 and 3, in Figures 13 and 14 respectively. The frames in each case correspond to 0, 10, 20, and 30 days after the spill. The two treated cases are shown; the difference in the untreated cases was a slight decrease in the areal extent of the 50 ppb contour line.

The major source of impact on eggs and larvae already present in the system at the time of the spill appears to result from spreading of the oil, advective transport being mutual. While the cloud is over the spawning area, additional mortality occurs due to eggs rising underneath the spill. One implication of this is that an oil spill occurring farther to the north and spreading to near maximum size before drift-

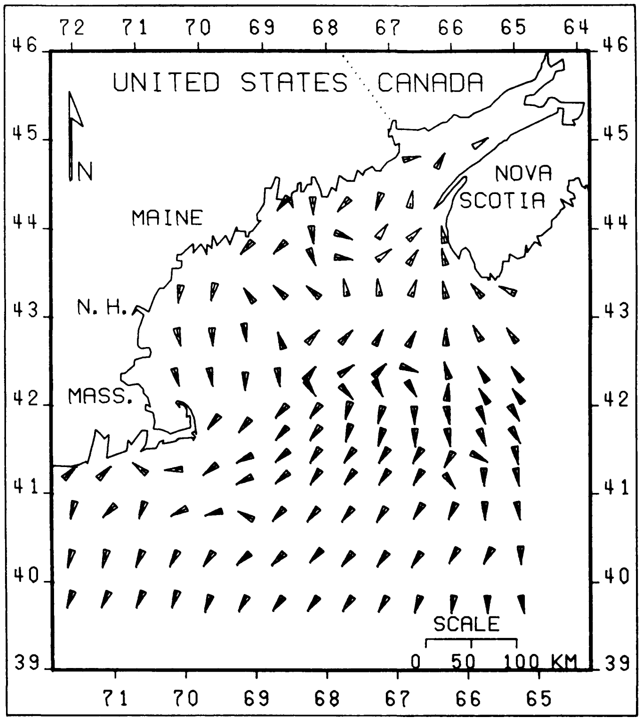


Figure 8a. Inferred winter velocity field[12]

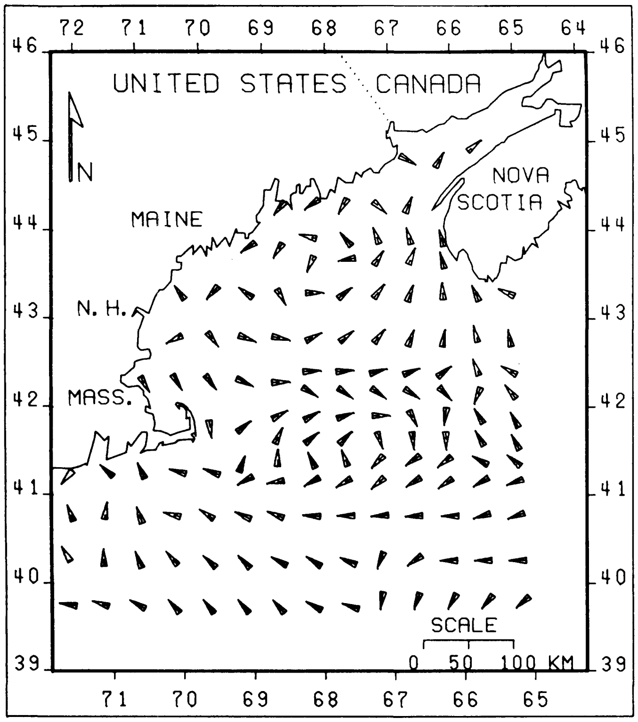


Figure 8b. Inferred spring velocity field[12]

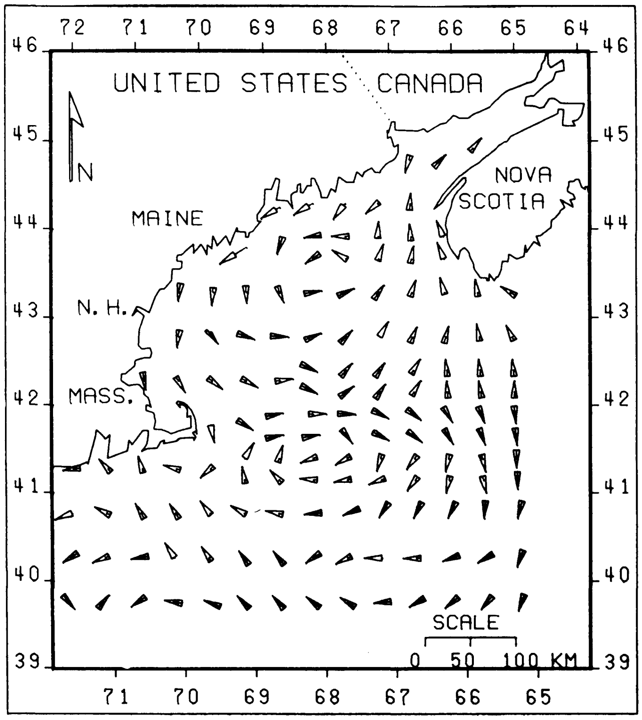


Figure 8c. Inferred summer velocity field[12]

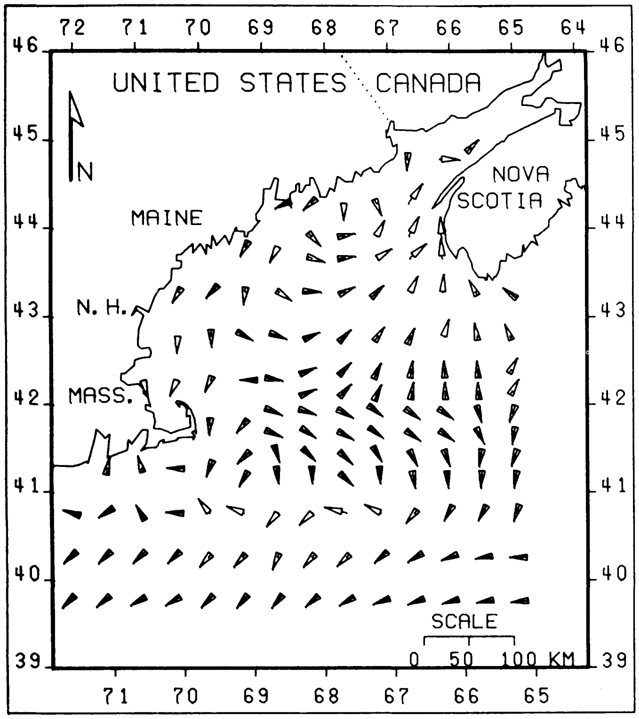


Figure 8d. Inferred fall velocity field[12]

ing over the spawning grounds would have a greater impact than the events simulated here. The differential advection between the surface and subsurface portions of the spill results from the effect of the wind.

Projection of modeled impact into the estimated commercial catch is shown in Figures 15 through 18. Figure 15 demonstrates the dependence of model behavior on the pre-recruit mortality coefficients (Figure 11). When density-dependent population control is weighted toward the pre-hatched stage, the model demonstrates an "over-damped" response to a perturbation, whereas increasing the post-planktonic effects of cannibalism (modes 1 and 3) results in residual oscillations. This is due to a direct adult-juvenile interaction formulation acting during the demersal (post-impact) stage, which effectively increases the slope of the theoretical stock-recruit curve at the replacement point, (defined as that point at which recruitment is just sufficient to maintain the given population size subject to the hypothesized mortality rates).

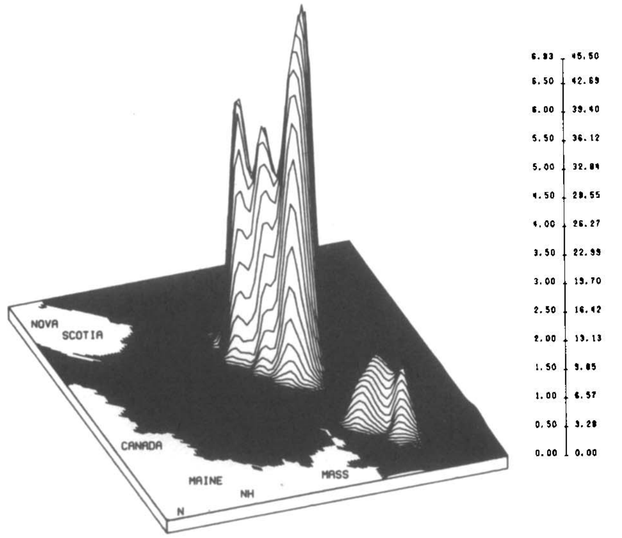


Figure 9a. Observed larval cod distribution for December, 1973 (vertical sacale: number of larvae per cubic meter)

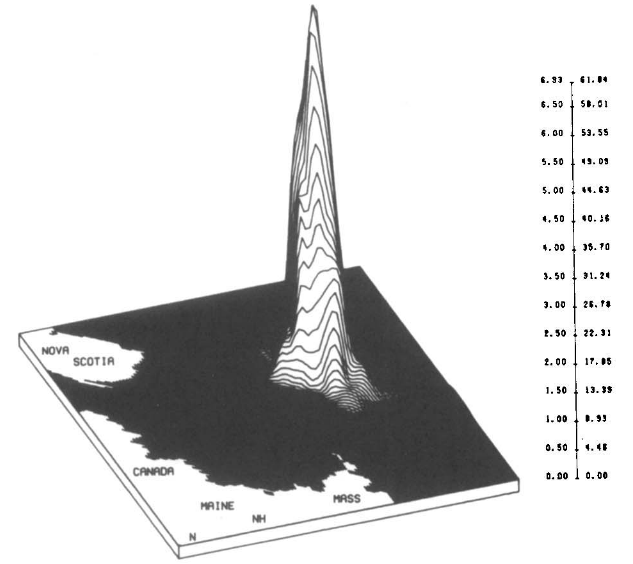


Figure 10a. Modeled larval cod distribution for December (vertical scale: number of larvae per cubic meter)

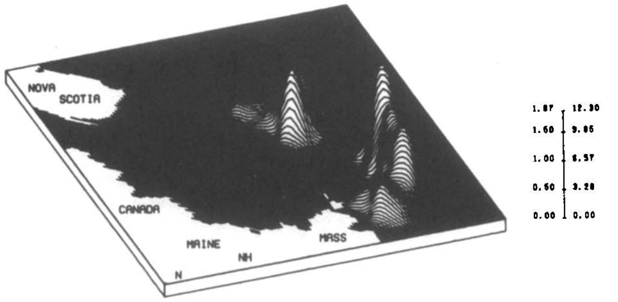


Figure 9b. Observed larval cod distribution for February, 1974 (vertical scale: number of larvae per cubic meter)

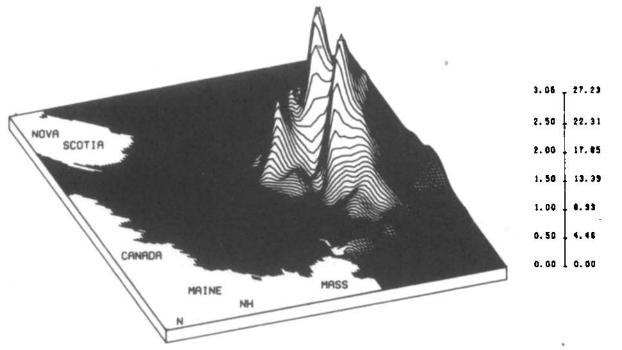


Figure 10b. Modeled larval cod distribution for February (vertical scale: number of larvae per cubic meter)

Oil dispersions in laboratory bioassays appear more toxic for longer periods of time than untreated oil confined largely to the surface.[37,67,69] The effect of treatment is to increase oil dissolution rates, raising the hydrocarbon concentration at depth, and decreasing the average drop size.[1,34] Although this leads to a more toxic situation in the short term, the duration of the impact could conceivably be lessened due to greater microbial utilization.[64]

Furthermore, it might be expected that dispersant addition in the field would lead to a more spatially-homogeneous distribution of hydrocarbons than an untreated case. These effects are not apparent from the results of these model runs for three reasons. First, the system is presently operating in only a two-dimensional mode. Second, the areal extent of the larval distributions precludes observations on scales of a few hundreds of meters to several kilometers—the scales of patchiness observed during the well-documented *Argo Merchant* spill.[46] Third, due to uncertainties in the available data, biodegradation has not been included in the oil fates program.

Because of the present tentative stature of the model system, no compeling conclusions can be inferred at this time regarding oil spill treatment decisions in the real world. The truth of this statement can be seen in a comparison of the differences in estimated catch loss between treated and untreated cases (Figures 15b and 16, and Figures 17 and 18) with the differences arising due to time of occurrence, in this case December and April. Although spawning is more intense just prior to the April spill (Figure 5), the ensuing impacts are smaller. Thus it appears that, for the area being modeled, details in the advective field may be more important than whether or not a dispersant is applied. In the present case, the effect noted is due to the longer residence time of the spill over the spawning area in December, as seen in Figures 13 and 14.

Comparing the effects of the treated and untreated cases (Figures 15 and 17 versus Figures 16 and 18) shows only small differences when projected into the domain of annual catch. This fact follows from the considerations mentioned above, plus density-dependent mortality factors which tend to compensate for reductions in numbers, further

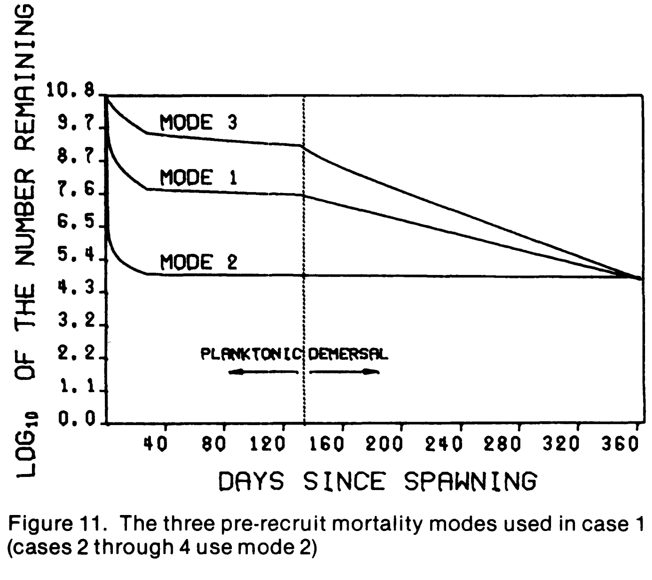


Figure 11. The three pre-recruit mortality modes used in case 1 (cases 2 through 4 use mode 2)

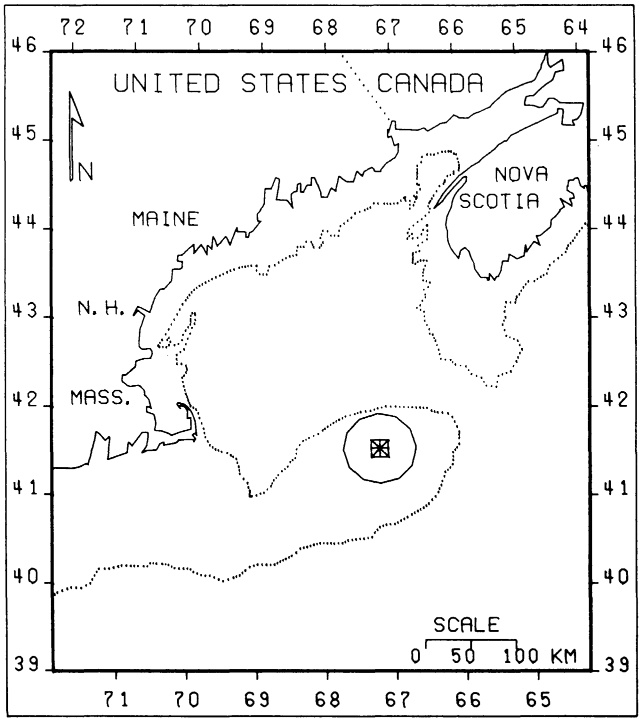


Figure 12. Location of the oil spill at the center of the spawning grounds (circle)

masking differences. That the impacts are not larger is also attributable to the simplifications in the vertical.

The results published here are highly preliminary, and are not indicative of actual consequences in the real world. Specific shortcomings in the model system that are currently being addressed include:

1. Insufficient resolution and coherence in both space and time of the advective velocity fields
2. A high degree of uncertainty associated with the pre-recruit mortality parameters
3. Uncertainties in the degree of relative sensitivity of the system to the mortality parameters, to anomalies in the advective field, to the stochastic diffusion process parameters, and to the toxicity assumptions
4. Uncertainty in oil entrainment rates and mechanisms

The real-world events under simulation here are extremely complex, so much so that actual evaluation of the impacts of an oil spill on a fishery is extremely difficult. If it is important to obtain an estimate of these impacts, then modeling is one of the better approaches currently available. Recognizing that simplifications will be necessary to render the problem tractable, the dilemma is then to determine how much complexity to remove, and from which aspects of the system. One must then make a series of estimates based on the best information available, and begin work with the expectation that a certain amount of iterative effort will be involved.

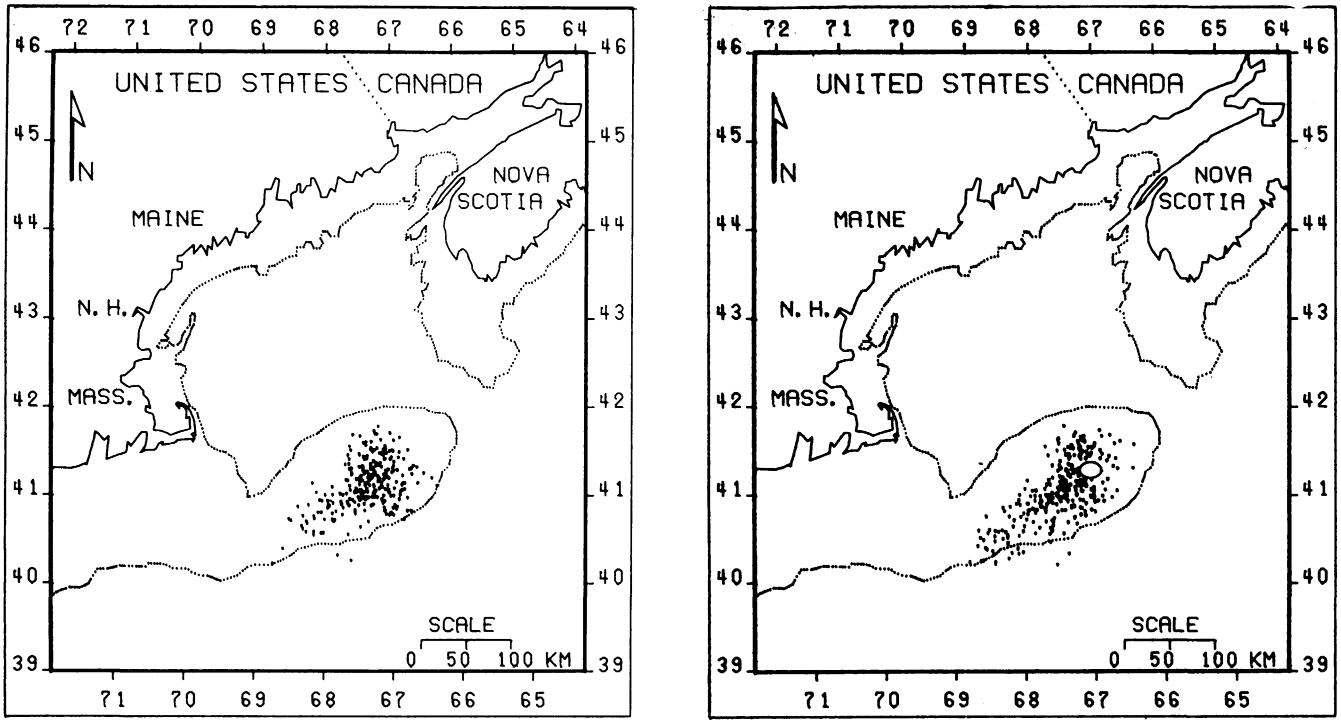
It was not foreseen, for example, that details within the advective field would greatly affect the area covered by a given concentration contour in the oil behavior model, and that the assumptions regarding toxicity thresholds would therefore prove extremely critical. It is important to determine more accurately the role of such factors in producing a specific result. In response to such lessons learned from these four simple runs, many improvements are now in progress. This report therefore only indicates the present state of the effort.

Acknowledgments

The authors wish to thank Kurt Hansen for assisting with the execution of graphics and for the velocity data preparation; Craig Swanson for writing the advection program used in the fisheries model; personnel at the National Marine Fisheries Center in Narragansett, Rhode Island for supplying data from their larval fish surveys, and programs URISYMVU and URISYMAP; and the University of Rhode Island Academic Computer Center. The U.S. Department of Energy, Division of Environmental Technology, provided the financial support to accomplish this effort under Contract No. E(11-1)4047. The responsibility for the material in this report belongs solely to the authors.

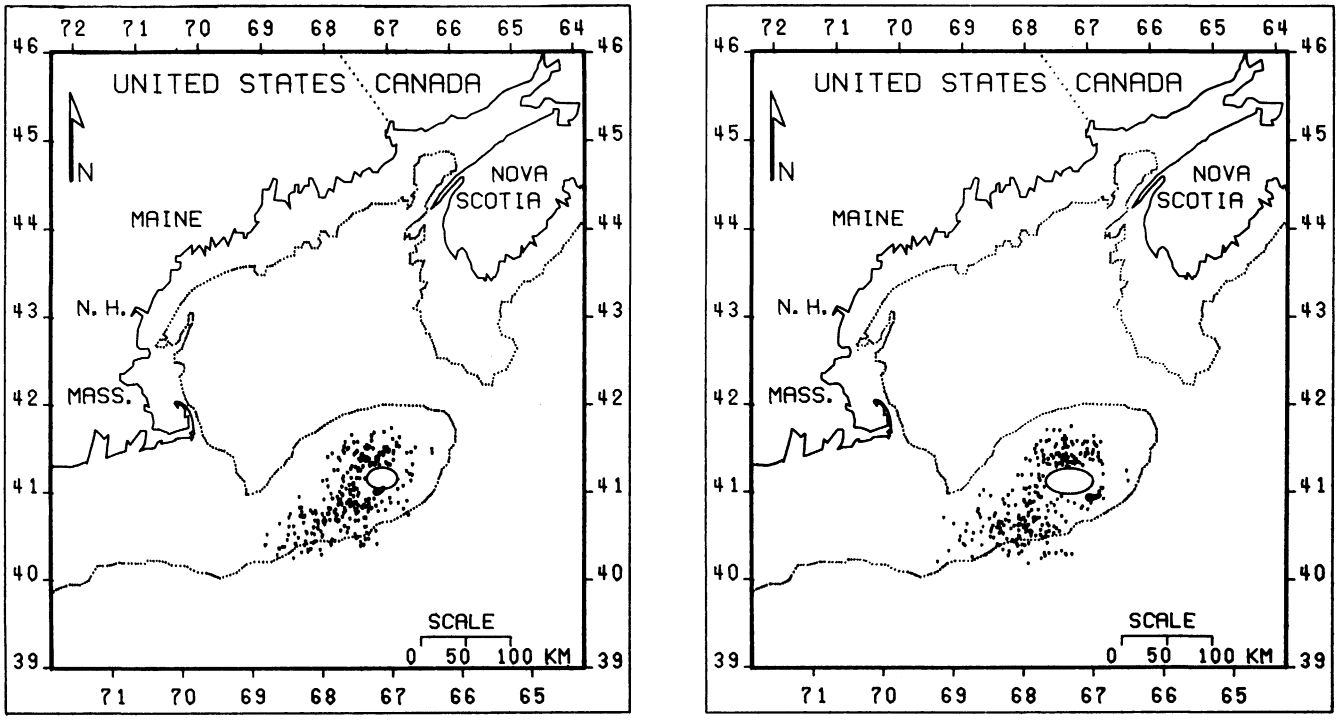
References

1. Ahmadjian, M., M. Brady, C. Brown, D. Goldfarb, and P. Lynch, 1978. Chemical analysis of water samples from mesoscale tanks in *Environmental Assessment of Treated Versus Untreated Oil Spills.* Second annual progress report, Contract No. e(11-1)4047. prepared for the U.S. Department of Energy, Washington, D.C.
2. Allen, R. L. and P. Basasibwaki, 1974. Properties of age structured models for fish populations. *Journal of the Fisheries Research Board of Canada.* v31, pp1119-1125
3. Andersen, K. P. and E. Ursin, 1977. The partitioning of natural mortality in a multispecies model of fishing and predation. in *Fisheries Mathematics.* J. H. Steele (ed). pp87-98.
4. Bartlett, M.S., and R. W. Hiorns (eds), 1972. The Mathematical Theory of Biological Populations. Academic Press, London
5. Beardsley, R. C. and B. Britman, 1973. New England Continental Shelf Dynamics Pilot Experiment. GFD Lab. Report, GFD/74-2. Massachusetts Institute of Technology-Woods Hole Oceanographic Institution
6. Beverton, R. E. and S. J. Holt, 1954. Notes on the Use of Theoretical Models in the Study of the Dynamics of Exploited Fish Populations. Miscellaneous Contribution No. 2. U.S. Fisheries Laboratory, Beaufort, North Carolina
7. Beverton, R. E. and S. J. Holt, 1957. On the dynamics of exploited fish populations. (Ministry of Agriculture, Fisheries, and Food of the U.K.) in *Fisheries Investigations.* Series II, v19
8. Bigelow, H. B. and W. C. Schroeder, 1953. Fishes of the Gulf of Maine. *Fisheries Bulletin.* U.S. Fish and Wildlife Service. U.S. Government Printing Office, Washington, D.C.
9. Bishop, J. M. and J. E. Overland, 1977. Seasonal drift on the middle Atlantic shelf. *Deep Sea Research.* v24, pp161-169
10. Bretschneider, C. L., 1974. On the influence of waves and currents on dispersion over the continental shelf. *Rapports Procedes Reunion Conseil Internationale Exploration De La Mer.* v167, pp13-20
11. Bumpus, D. F. and C. F. Day, 1957. Drift Bottle Records for the Gulf of Maine and Georges Bank, 1931-1956. Special Scientific Report on Fisheries No. 242. U.S. Fish and Wildlife Service, Washington, D.C. 61p
12. Bumpus, D. F., 1973. A Description of the Circulation on the continental shelf of the east coast of the United States. *Progress in Oceanography.* Pergamon Press, New York. v6, pp111-157
13. Bumpus, D. F., and L. M. Lazier, 1965. Surface circulation on the continental shelf off eastern North America between Newfoundland and Florida. in *Serial Atlas of the Marine Environment, Folio 7.* American Geographic Society
14. Clayden, A. D., 1972. Simulation of the Changes in Abundance of the Cod (*Gadus morhua* L.) and the Distribution of Fishing in the North Atlantic. (Ministry of Agriculture, Fisheries, and Food of the U.K.) in *Fisheries Investigations.* Series II, v27
15. Coastal Resources Center, 1977. Fishing and Petroleum Interactions on Georges Bank. Energy Tech. Report 77-1. prepared for the Northeast Regional Commission
16. Colton, J. B., Jr., and R. R. Byron, 1977. Gulf of Maine—Georges Bank Icthyoplankton Collected on ICNAF Larval Herring Surveys, September 1971-February 1975. NOAA Technical Report. NMFS-SSRF-717. U.S. Department of Commerce
17. Colton, J. B., Jr., and J. M. Onge, 1974. Distribution of fish eggs and larvae in continental shelf waters, Nova Scotia to Long Island. in *American Geographic Society Atlas of the Marine Environment.* Folio 23
18. Colton, J. B., Jr., and R. F. Temple, 1961. The enigma of Georges Bank spawning. *Limnology and Oceanography.* v6, n3, pp280-291
19. Csanady, G. T., 1974. Barotropic currents over the continental shelf. *Journal of Physical Oceanography.* v4, n3, pp357-371



0 DAYS AFTER THE OILSPILL
(JULIAN DAY 350)

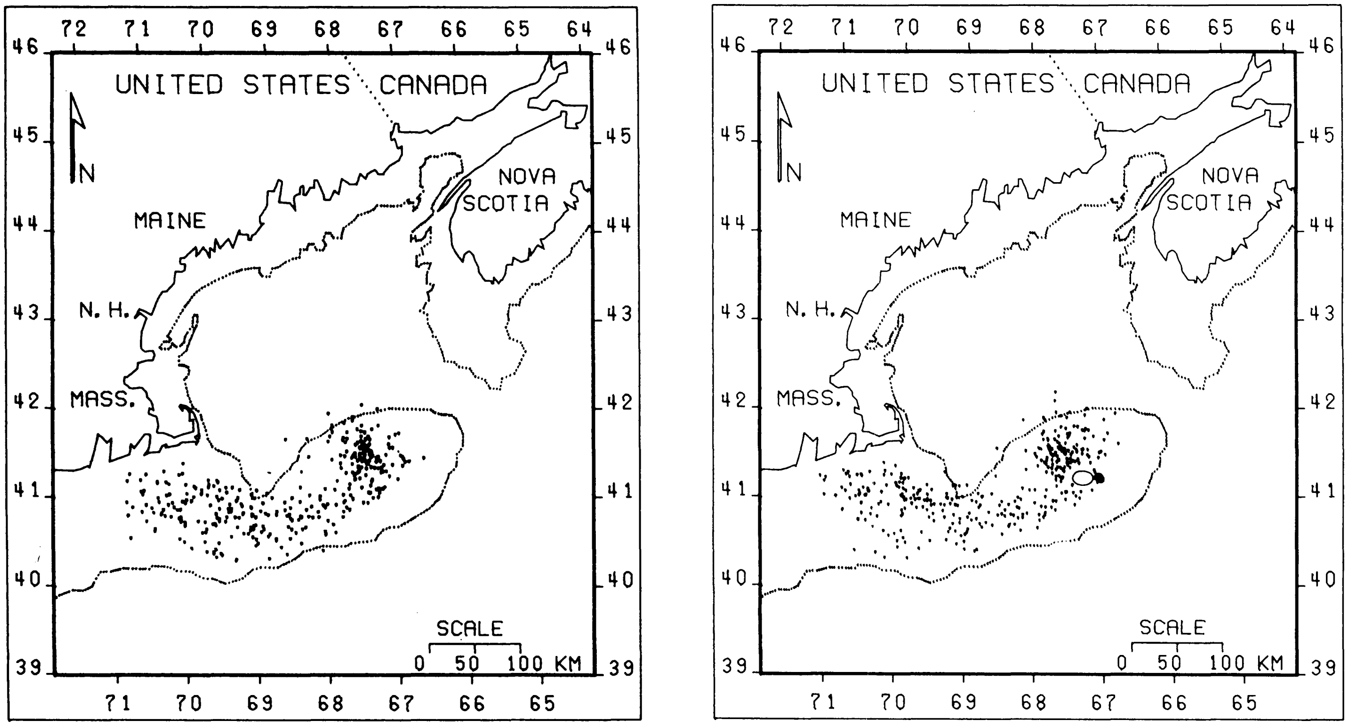
10 DAYS AFTER THE OILSPILL
(JULIAN DAY 360)



20 DAYS AFTER THE OILSPILL
(JULIAN DAY 5)

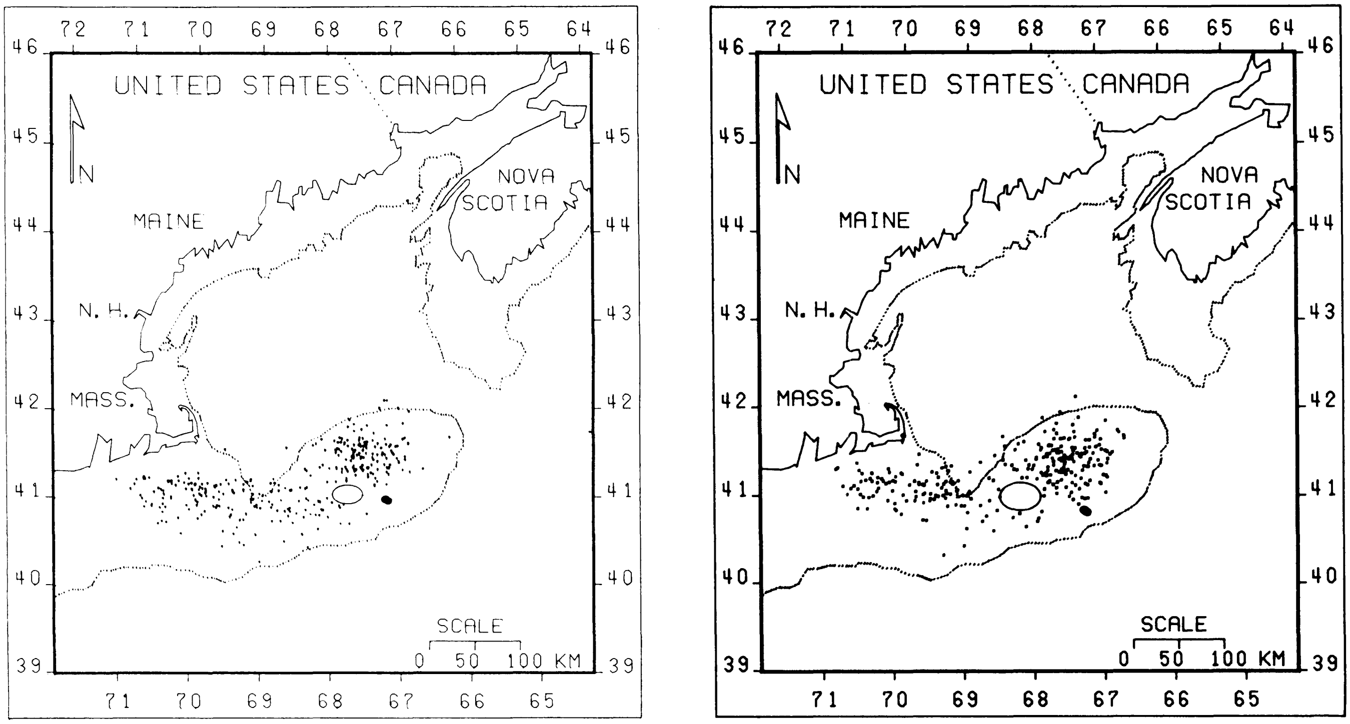
30 DAYS AFTER THE OILSPILL
(JULIAN DAY 15)

Figure 13. Case 1 (December, treated): distribution of eggs, larvae, subsurface (open ellipse, 50 ppb contour), and surface (dark area) hydrocarbons at 0, 10, 20, and 30 days after the spill



0. DAYS AFTER THE OILSPILL
(JULIAN DAY 90)

10 DAYS AFTER THE OILSPILL
(JULIAN DAY 100)



20 DAYS AFTER THE OILSPILL
(JULIAN DAY 110)

30 DAYS AFTER THE OILSPILL
(JULIAN DAY 120)

Figure 14. Case 3 (April, treated): distribution of eggs, larvae, subsurface (open ellipse, 50 ppb contour line), and surface (dark area) hydrocarbons at 0, 10, 20, and 30 days after the spill

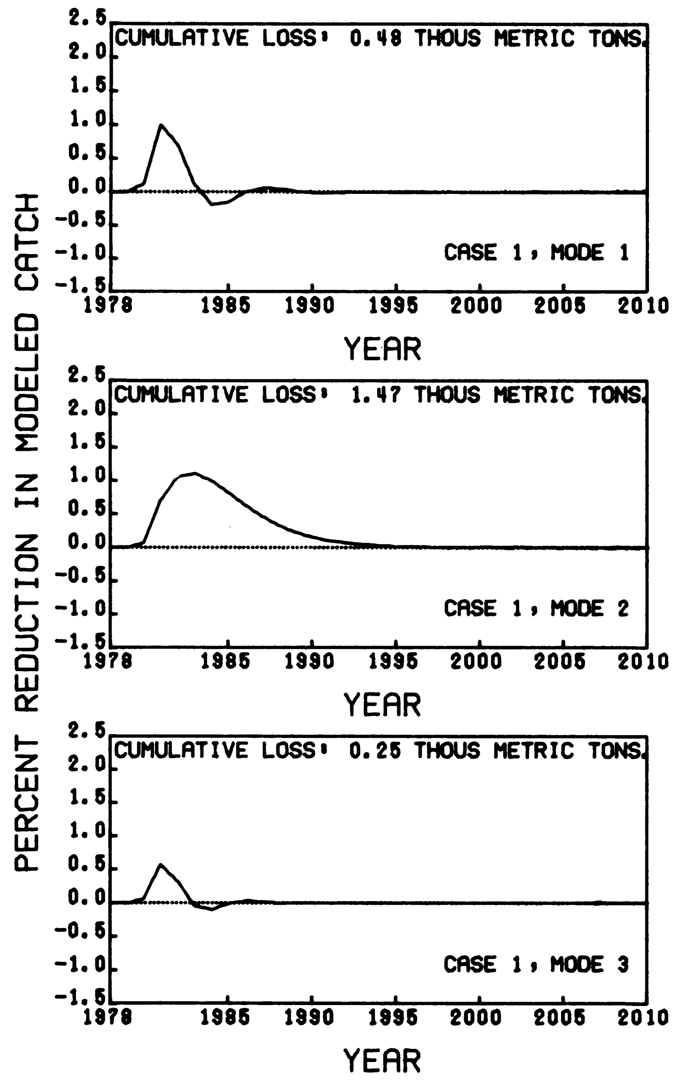


Figure 15. Comparison of impact estimates for case 1, using three different mortality curves as shown in Figure 11

20. Csanady, G. T., 1973. Turbulent Diffusion in the Environment. D. Reidel Publishing Co., Rordrecht, Holland
21. Daan, N., 1973. Results of Dutch Cod Egg Surveys in the North Sea in 1973. CM 1973/F:37. International Council for the Exploration of the Seas
22. Daan, N., 1974. Results of a Study of Consumption and Production of North Sea Cod. CM/F:38. International Council for the Exploration of the Seas

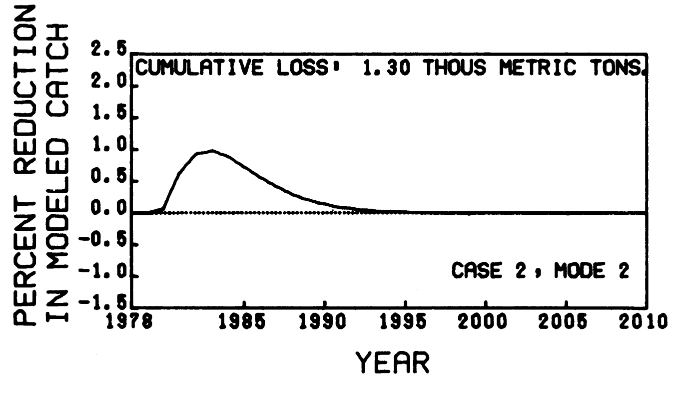


Figure 16. Impact estimate for case 2

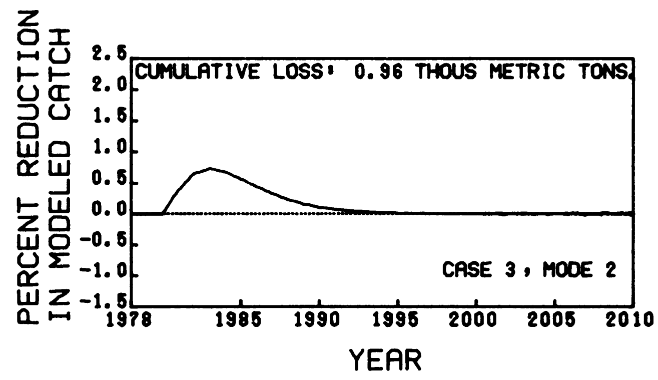


Figure 17. Impact estimate for case 3

23. Dannevig, H., 1895. The Influence of Temperature on the Development of Eggs of Fishes. Thirteenth Annual Report of the Fisheries Board of Scotland. pp147-152
24. Fisher, H. B., 1978. On the tensor form of the bulk dispersion coefficient in a bounded skewed shear flow. *Journal of Geophysical Research.* v83, pp2373-2375
25. Garrod, D. J., 1967. Population dynamics of the Arcto-Norwegian cod. Journal of the Fisheries Research Board of Canada. v24, n1, pp145-190
26. Garrod, D. J., 1977. The north Atlantic cod. in *Fish Population Dynamics.* J. A. Gulland (ed). John Wiley and Sons, New York. pp216-239
27. Gulland, J. A., 1964. Survival of the Youngest Stages of Fish, and Its Relation to Year-class Strength. Special Publication No. 6. International Commission for Northwest Atlantic Fisheries. pp363-372
28. Gulland, J. A. (ed), 1977. Fish Population Dynamics. John Wiley and Sons, New York
29. Hall, C. A. S. and J. W. Day, Jr. (eds), 1977. Ecosystem Modeling in Theory and Practice: An Introduction with Case Histories. John Wiley and Sons, New York
30. Hannesson, R., 1975. Fishery dynamics: A North Atlantic cod fishery. *Con. J. Econ.* v8, pp151-173
31. Heyerdahl, E., and P. Wood, 1976. Data Summaries Prepared for Subarea 5 Cod Assessment. Working paper 76/iV//70. International Commission for Northwest Atlantic Fisheries
32. Jones, R. and W. Hall, 1973. A simulation model for studying the population dynamics of some fish species. in *The Mathematical Theory of Biological Populations.* Bartlett and Hiorns (eds). pp35-39
33. Kelly, G. F., and A. M. Barker, 1961. Vertical distribution of young redfish in the Gulf of Maine. *Rapport et Procès-Verbaux Réunions Conseil Internationale pour l'Exploration de la Mer.* v150, pp220-233
34. Kim, T., M. Cherian, and W. Jasper, 1978. Drop size distribution and mixing energy. in *Environmental Assessment of Treated Versus Untreated Oil Spills.* Second interim progress report, Contract No. E(11-1)4047. prepared for U.S. Department of Energy

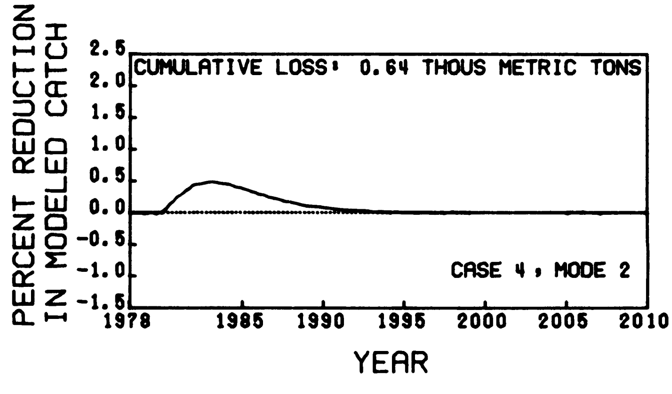


Figure 18. Impact estimate for case 4

35. Kraus, E. B. (ed), 1977. Modelling and Prediction of the Upper Layers of the Ocean. Pergamon Press, Oxford
36. Kunhold, W. W., 1969. Effects of Water Soluble Substances of Crude Oil on Eggs and Larvae of Cod and Herring. CM1969/E17. presented at Copenhagen International Council for Exploration of the Seas, Fish. Imp. Comm.
37. Kunhold, W. W., 1972. The influence of crude oils on fish fry. in *Marine Pollution and Sea Life.* M. Ruivo (ed). Fishing News (Books) Ltd., Surrey. pp318-322
38. Kunhold, W. W., 1977. Effects of the Water Soluble Fraction of a Venezuelan Heavy Fuel Oil (No. 6) on Cod Eggs and Larvae. International Council for Exploration of the Seas, Fisheries Imp. Comm. (mimeo)
39. Laurence, G. C. and C. A. Rogers, 1976. Effects of temperature and salinity on comparative embryo development and mortality of cod (*Gadus morhua* L.) and haddock (*Melangrammus aeglefinus* L.). *Journal of the International Council for Exploration of the Seas.* v36, n3, pp220-228
40. Lotka, A. J., 1925. Elements of Physical Biology. Williams and Wilkins Co., Baltimore
41. Miller, D., J. B. Colton, Jr., and R. R. Marak, 1963. A study of the vertical distribution of larval haddock. *Conseil Internationale pour l'Exploration de la Mer, Journal du Conseil.* v28, n1, pp37-49
42. Michael, A. D., 1977. Effects of petroleum hydrocarbons on marine populations and communities. in *Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms.* D. A. Wolfe (ed). Pergamon Press, New York. pp129-137
43. Meek, A., 1924. The Development of the Cod (*Gadus callarius* L.). Ministry of Agriculture, Fisheries, and Food of the U.K. *Fisheries Investigations.* Series II. v7, n1, pp1-26
44. Moore, S. F. and R. L. Dwyer, 1974. Effects of oil on marine organisms: A critical assessment of published data. *Water Research.* v8, pp819-827
45. National Oceanic and Atmospheric Administration, 1976. Fishery Statistics of the U.S. National Marine Fisheries Service, Washington, D.C.
46. National Oceanic and Atmospheric Administration, 1977. The Argo Merchant Oil Spill: A Preliminary Report. Department of Commerce, NOAA, Washington, D.C.
47. New England Regional Commission, 1977. Fishing and Petroleum Interactions on Georges Bank. Technical Report No. 77-1. U.S. NERC, Energy Program
48. Nihoul, J. C. J. (ed), 1976. Continental Shelf Dynamics Seventh Liege Colloquium on Ocean Hydrodynamics. Siege De La Societe Royale des Sciences de Liege, Belgium
49. Nikolskii, G. V., 1965. Theory of Fish Population Dynamics. Oliver and Boyd, Edinburgh
50. Okubo, A., 1974. Diffusion Induced Instability in Model Ecosystems: Another Possible Explanation of Patchiness. Technical Report No. 86. Chesapeake Bay Institute
51. Pentilla, J. A. and V. M. Gifford, 1976. Growth and mortality rates for cod from the Georges Bank and Gulf of Maine areas. *Research Bulletin.* International Commission for Northwest Atlantic Fisheries. n12, pp29-36
52. Pielou, E. C., 1969. An Introduction to Mathematical Ecology. Wiley Interscience, New York
53. Pielou, E. C., 1977. Mathematical Ecology, Wiley Interscience, New York
54. Reed, M. and M. L. Spaulding, 1978. An oilspill-fishery interaction model. Part X in *Environmental Assessment of Treated Versus Untreated Oil Spills: Second Interim Progress Report.* Contract No. E(11-1)4047. Department of Energy, Washington, D.C.
55. Richardson, L. F., 1926. Atmospheric diffusion shown on a distance neighbor graph. *Proceedings of the Royal Society.* v110, p709
56. Ruivo, M. (ed), 1972. Marine Pollution and Sea Life. Fishing News (Books) Ltd., Surrey
57. Serchuk, F. M., 1978. Summary of Atlantic Cod Assessment for Public Hearings on Groundfish Fishery Management Plan. National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Woods Hole, Massachusetts. Unpublished (mimeo)
58. Serchuk, F. M. and S. H. Clark, 1977. Analysis of the Georges Bank and Gulf of Maine Cod Stocks. NOAA, National Marine Fisheries Service, Woods Hole, Massachusetts
59. Serchuk, F. M., P. W. Wood, and B. E. Brown, 1978. Atlantic Cod (*Gadus morhua*): Assessment and Status of the Georges Bank and Gulf of Maine Stocks. Reference No. 78-03 National Marine Fisheries Service, Woods Hole, Massachusetts
60. Silliman, R., 1969. Analog computer simulations and catch forecasting in commercially fished populations. *Transactions of the American Fisheries Society.* v3, pp560-569
61. Silliman, R., 1966. Analog Computer Models of Fish Populations. *Fisheries Bulletin.* Bureau of Commercial Fisheries, Washington, D.C. v66, n1, pp31-46
62. Steele, J. H. (ed), 1977. Fisheries Mathematics. Academic Press, London
63. Steele, J. H., 1977. Ecological modelling of the upper layers. in *Modelling and Prediction of the Upper Layers of the Ocean.* E.B. Kraus (ed). Pergamon Press, Oxford. pp243-250
64. Traxler, R. W. and L. S. Bhattacharya, 1977. Effect of a chemical dispersant on microbial utilization of petroleum hydrocarbons. *Williamsburg Conference Proceedings.* American Society For Testing and Materials
65. Walford, L. A., 1938. Effect of currents on distribution and survival of the eggs and larvae of the haddock (Melangrammus aeglefinus) on Georges Bank. *Fisheries Bulletin.* Bureau of Commercial Fisheries, Washington, D.C. No. 29
66. Walters, C. J., 1969. A generalized computer simulation model for fish population studies. *Transactions of the American Fisheries Society.* v98, pp505-512
67. Wilson, K. W., 1977. Acute toxicity of oil dispersants to marine fish larvae. *Marine Biology.* v40, pp65-74
68. Wilson, K. W., 1974. Toxicity testing for ranking oils and dispersants. pp. 11-22 in *Ecological Aspects of Toxicity Testing of Oils and Dispersants.* Beynon and Cowell (eds). John Wiley and Sons, New York. pp11-22
69. Wilson, K. W., 1972. The toxicity of oil spill dispersants to the embryos and larvae of some marine fish. in *Marine Pollution and Sea Life.* M. Ruivo (ed). Fishing News (Books) Ltd., Surrey. pp318-322
70. Wise, J. P., 1963. Cod groups in the New England area. *Fisheries Bulletin,* Bureau of Commercial Fisheries, Washington, D.C. v63, n1, pp189-203
71. Wise, J. P., 1962. Bibliography on the biology of cod *(Gadus morhua)* and related species. *Fisheries Bulletin.* U.S. Fish and Wildlife Service. v215, n62, pp483-538
72. Wise, J. P., 1961. A synopsis of biological data on Cod, *Gadus morhua.* Fisheries Division, Biological Branch, U.N. Food and Agriculture Organization, Rome
73. Wolfe, D. A. (ed), 1977. Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and organisms. Pergamon Press, New York
74. Workshop on Imputs, Fates, and Effects of Petroleum in the Marine Environment, 1975. Petroleum in the Marine Environment. National Academy of Sciences, Washington, D.C.
75. Yudelson, J., 1967. A Survey of Ocean Diffusion Studies and Data. Memorandum 67-2. California Institute of Technology.