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ECOSYSTEMS DYNAMICS, EASTERN BERING SEA

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I. Summary of objectives, conclusions and implications with respect to OCS oil and gas development

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II. Introduction

There is an obvious need for multispecies analyses of living marine resources. Such analyses require among other things, new modeling techniques for ecosystem models, which have not been developed in the past and therefore must be designed, tested and evaluated concurrently with the model design, programming and testing.

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The model is expected to demonstrate the interdependence of major biological components and to assess the effects of physical-chemical factors that do or could alter the existing biological interdependencies.

C. Relevance to problems of petroleum development

Attainment of stated objectives will permit assessing cause and effect changes on the biota as a result of favorable or unfavorable environmental conditions, and man's fishing activities, in contrast to changes that may be induced as a result of normal petroleum development or catastrophic accidents.

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The present study area encompasses the eastern Bering Sea from long. 180° to the west Alaska coast northward of the Alaska peninsula and Aleutian Islands to approximately lat. 65°N (Figure 1). Thus, it includes the Bristol Bay, St. George and Navarin Basins, as well as Norton Sound. The area can be enlarged to include the Chukchi Sea or reduced to encompass only individual basins.

V. Source, methods and rationale of data collections

No field data are collected. Model input data are obtained from the literature and from various unpublished sources.

VI. Results

For the first quarter of 1977 the DYNUMES model was reprogrammed and extended to include 25 major components of the marine ecosystem. The program is now of considerable size, so that locally available computers (CDC 6400 and CYBER 73) are at times used to capacity. The model is being quantitatively tuned (adjusted). No "production" runs have been made within the complete model, therefore no detailed results can be reported at this time. Preliminary results, however, show that most of the qualitative and quantitative dynamics of the marine ecosystem (e.g. the interactions between species, between species and environment, and the effects of man's actions on the species and ecosystems a total) can now be studied and quantified.

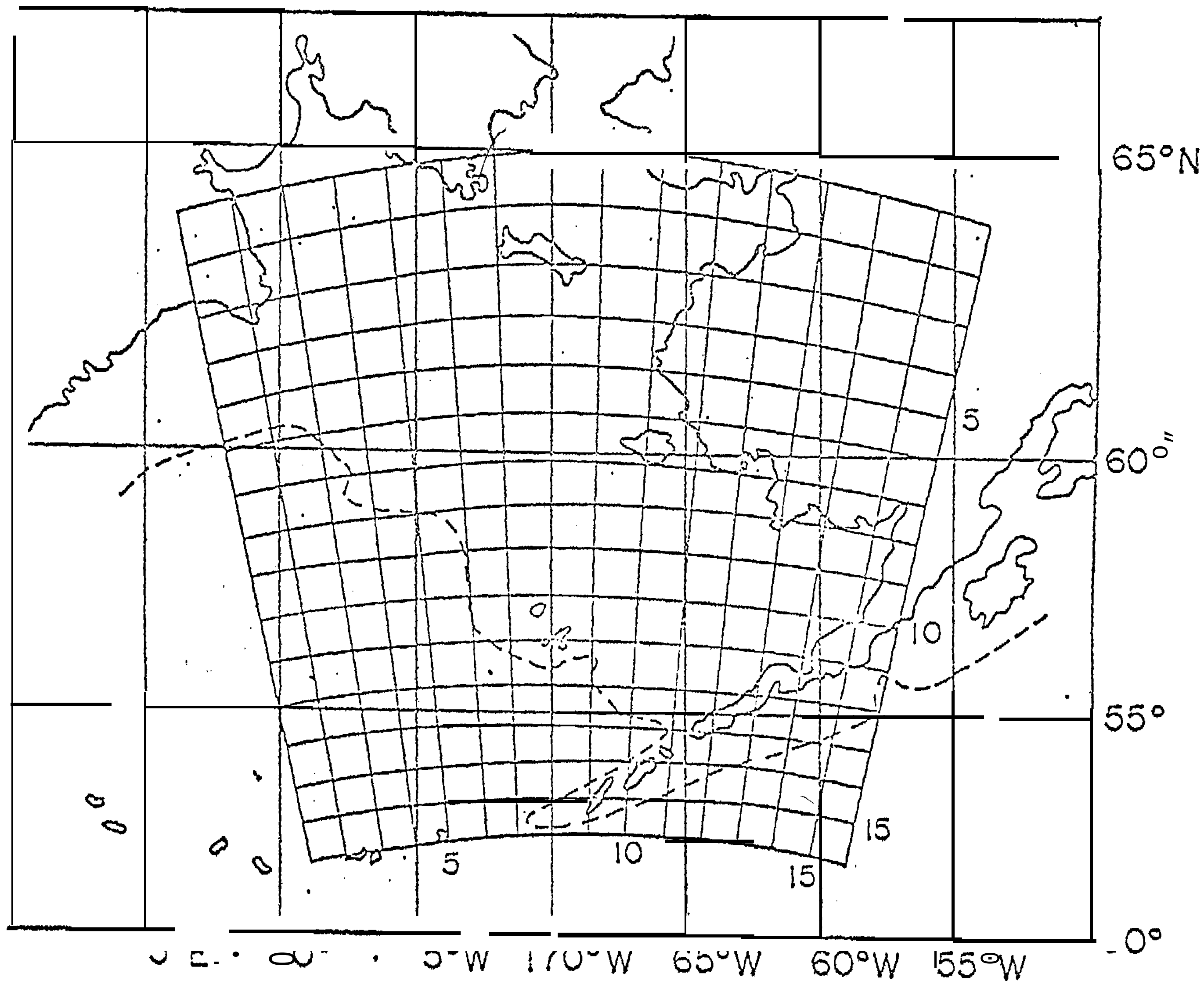

Figure .--Model grid (16 X 16).

'The 25 major components incorporated in the existing model are: (a) Mammals: fur seal, sea lion, bearded seal, harbor seal, ring and ribbon seals, walrus, baleen whales, toothed whales; (b) Birds: shearwater, murre, and other marine birds; (c) Fish: yellowfin sole, other flatfish, other demersal fish, pollock - 3 size groups, other gadids, herring, other pelagic fish, squids; (d) Benthos; (e) Plankton: euphausids, copepods, phytoplankton.

VII. Discussion

Most of the modeling approaches and techniques used in our dynamic four-dimensional ecosystem model are new in biological modeling. The conventionally used two-dimensional modeling, starting either with nutrients and/or phytoplankton has not lead to any useful results in the past. Our model starts from the opposite end of the food web, i.e. with mammals and birds. The model uses the accumulated knowledge on marine ecology in direct form, and interactions can be quite different from one group of species and/or processes to another. It has become increasingly apparent that although logical results are obtained, these are essentially new concepts and there is a need for extended field studies to demonstrate the validity of model results before one can expect a universal acceptance. Furthermore, we must document the model, its flexibility and sensitivity in greater detail in forthcoming technical reports.

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Our DYNUMES model for the eastern Bering Sea has demonstrated its utility in quantitative simulation of processes in the total marine ecosystem and in assessment of the impacts of man's activity (e.g. offshore oil development, fisheries, etc.) on the marine ecosystem and its components

Among numerous tentative conclusions, the following, based or-I existing data and techniques, demonstrate the eventual utility of model results:

1. The marine ecosystem has no real stability, but most of the components fluctuate around specific local long-term means.

2. There are natural, quasi-cyclic changes in *the* ecosystem. For example, the biomass of the pollock in the eastern Bering Sea has a ca 12 year period of fluctuation, whereby the quantitative relations between lowest and highest biomasses during this period is ca 1:3. These quasi-cyclic changes are caused by cannibalism found in older pollock.

3. Relatively intensive fishery on pollock removes larger, older (and cannibalistic) fish and may be beneficial in keeping up higher standing crop of pollock.

4. The consumption of fish by mammals in the eastern Bering Sea appears higher than the total commercial catch.

5. The availability of food is a limiting factor on nearly all levels in the ecosystem and starvation may be common.

6. Available, past quantitative data on the standing stocks of zooplankton appears far too low; apparently present sampling methods do not capture euphausids quantitatively.

7. Very little information is available on the bulk of the biomass (< 50%) of most fish species, the prefishery juveniles.

8. Ecosystem internal consumption appears nearly an order of magnitude higher than the total commercial catch.

IX. Needs for further study

Except for further sub-divisions (or expansion} of the benthos submodel, we anticipate that the model scheduled for completion this fall will be adequate for evaluation of effects of increased or decreased fishing effort or shifts in areas of exploitation of present fisheries. However, before we have an adequate ecosystem model that will account for environmental changes (e.g. variability in the extent of ice cover and subsequent shifts in the location of temperature regimes) on the displacement of stocks and subsequent interactions (crowding or dispersal) it will be necessary to incorporate a functional hydrodynamical-numerical (H-N) model with the present predominantly biomass data. We have several options - we can devise our own H-N model, incorporate one under development through OCSEAP funding (Rand Corporation or Gait models], or develop an optimized model incorporating the best attributes of all of the above. In order to accomplish this, funding for RU-77 for 1978 must be restored to $100 K. The attached report (Laevastu, T., and F. Favorite - Summary review of Dynamical Numerical Marine Ecosystem Model, In: Proceedings of the NMFS/ODS workshop on climate and fisheries, April 26-29, 1976, Washington, D.C., October 1976) indicates some of the techniques to be incorporated.

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B. Problems encountered/recommended changes

None except in (b) above

C. Estimate of funds expended

$25 K

Figure 2 Milestone chart

		Month 1976 10	11	12	1977 1	2	3	4	5	6	7	8	9
(A) 1.	Flow diagrams, restrained functions, synthesis and quantification of input data, display subroutines	X	----	----	----	----	----	----	----	----	----	----	X
(A) 2.	Programming and debugging of submodels		X	----	----	----	X						
(A) 3.	Mammal submodel		X										
(A) 4.	Bird submodel			X									
(A) 5.	Fish submodel				X								
(A) 6.	Plankton submodel					X							
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(M/S) 8.	First test of total systems model									(X)			
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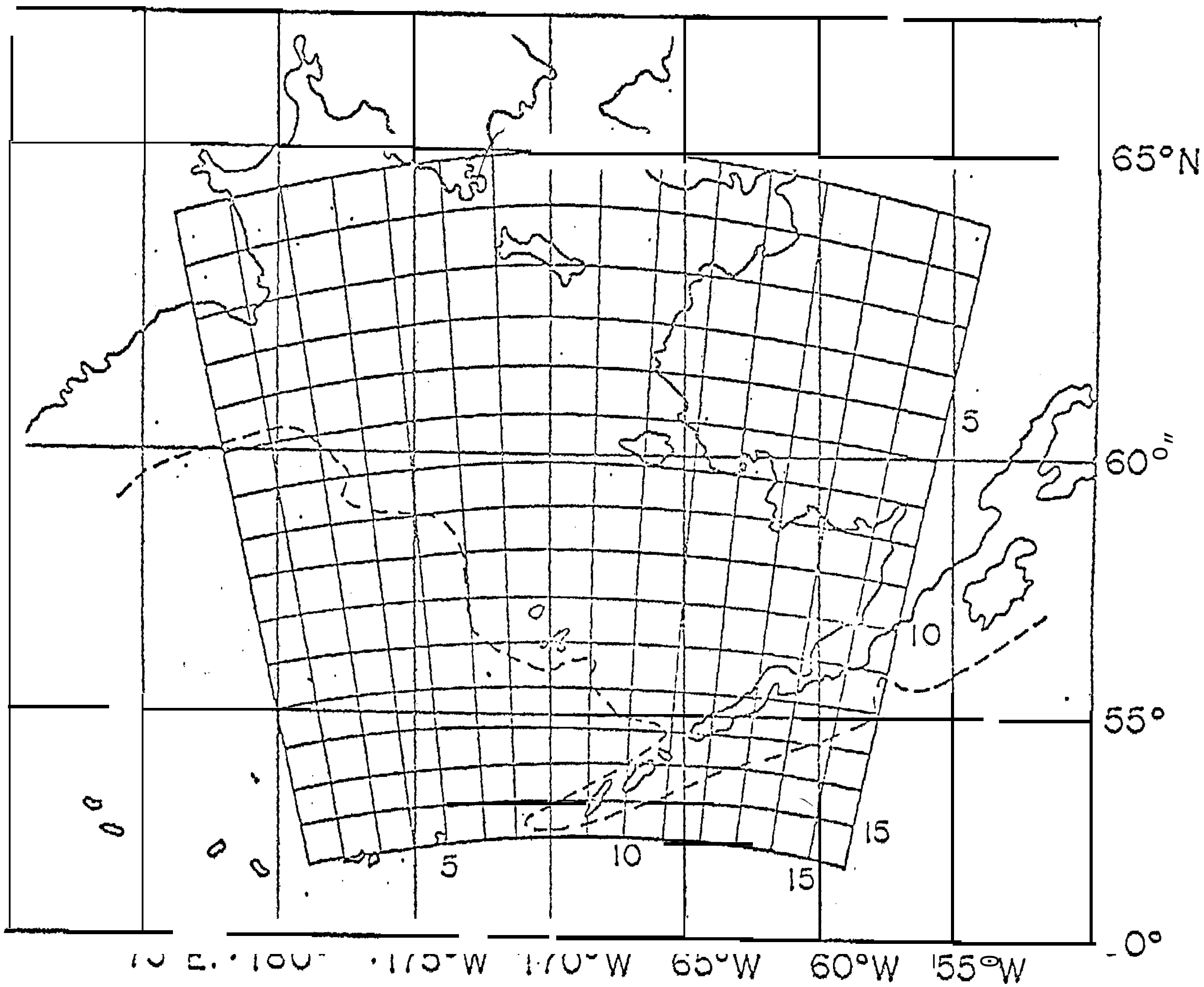

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INTRODUCTION

Environmental Changes as Dynamic Forces in a Marine Ecosystem

Numerous studies show that changes in the marine environment, such as year-to-year anomalies or long-term changes of temperature in surface layers, have profound effects on marine ecosystems in higher latitudes. These especially affect the abundance and distribution of some exploited species (fish) which occur in abundance near their natural environmental boundaries (e.g., temperature boundaries). For a sound management of marine resources, it is necessary to account for both the effect of man and the effects of environmental changes, and to evaluate qualitatively each effect and its interactive feedback to the other. Furthermore, it has been fully recognized that marine ecosystems are not static, but highly dynamic. For example, a change in one component of the system can cause a chain reaction and influence several other components; also a niche in the system vacated by a decrease of population of one species can be occupied by another species. The marine ecosystem is internally highly competitive with respect to food resources and "living space." Thus, to understand and manage this system, it is necessary to design a system model complete with all of its intricate interactions.

To illustrate some of the introductory statements, especially with respect to the effects of environment on various components of a marine ecosystem, we cite the example of the slight warming of Greenland's coastal waters in the 1940's. The occurrence of greater quantities of cod in these waters coincided with this warming. Similarly, a decrease of the cod abundance coincided with the long-term cooling of Greenland water in the 1960's. This example has been thoroughly studied and documented, particularly by the late Danish fisheries biologist Wedell-Taning. Cod in Greenland waters occurs near its natural environmental distribution boundary, which is determined by temperature. Thus, any relatively small, long-term temperature change near such distributional boundaries can have pronounced effects on the occurrence and abundance of cod or other similarly reacting species. Another case of long-term change of abundance of a species, which might have been caused by a combination of intensive fishery intervention and the effect of unfavorable environment during and after spawning, is the case of the California sardine. These influences resulted in a succession of bad year classes, as explained by Murphy and others. In this case, the niche vacated by sardine was occupied by anchovy--an ecologically similar species.

Figures 1 and 2 give examples of the effects of year-to-year local environmental anomalies for cod and haddock. Optimum temperature" for spawning of Icelandic cod is 3 to 5°C (fig. 1). If there is a positive temperature anomaly on the spawning grounds during the spawning season, the spawning area may be displaced into deeper, cooler layers, which are found usually at the continental slope. First, this displacement affects the fishery because the fish might be aggregating too deep to be accessible to conventionally used gear or the ground on the slope might be rough, hence unsuitable for trawling operations, Second, the fish might spawn in a relatively limited area (because of the limited area on the slope between optimum isotherms). The result might be a poor year class because of excessive consumption of eggs by predators or unfavorable drift of the hatched larvae into areas where proper food is unavailable. The latter aspect of larval drift from spawning grounds displaced because of temperature anomalies is illustrated on figure 2 with Georges Bank haddock. In this case, a poor year class results as a greater portion of the larvae are carried away during a cold anomaly year by the strong, warm Gulf Stream, which is characteristically low in food organisms for these larvae.

Conditions in the eastern Bering Sea are, in several aspects, similar to those depicted in figures 1 and 2, except instead of cod and haddock the main commercially important gadid species is pollock. Furthermore, the eastern Bering Sea has a wide continental shelf with a relatively steep continental slope to the west. This slope is a productive area, partly because of intensive mixing of the water by a narrow, strong northward current. Several fish species have their spawning grounds at the southwestern part of the eastern Bering Sea continental shelf, and eggs and larvae are carried along the slope and over the shelf into productive waters during the summer.

Our main purpose is to present a brief description of the ecosystem model of the eastern Bering Sea under development at Northwest Fisheries Center in Seattle. Some specific components accounting for environmental effects in a complete dynamic numerical marine ecosystem model are described later in this paper. Some aspects of the local marine ecosystems and environment interactions make the eastern Bering Sea area suitable for testing a complete dynamic ecosystem model for studying variable environmental effects. First, this area contains the northern environmental tolerance boundary of many commercially exploited fish species, This "boundary," which varies seasonally, year to year, and over longer periods, affects the distribution and abundance of species in this area. Furthermore, intensive fishing and planned offshore oil exploration in the area might affect parts of the ecosystem. The abundance of fish in the Bering Sea supports an abundance of marine mammals that compete with man for the living marine resources. In fact, marine mammals consume more fish in the Bering Sea than are currently caught commercially, even though most commercial species seem to be already nearly overfished.

An initial submodel of some species of marine mammals (fur seal and bearded seal) and birds (shearwater and murres) and their principal food items (pollock, herring, and macroplankton) is in advanced state of programming.

Definition of a Dynamic Marine Ecosystem Model

A dynamic marine ecosystem model permits simulation of the statics and dynamics of standing crops of various species and groups of species (i.e., abundance and distribution) in space and time as affected by interspecies interactions, such as predation, environmental factors such as temperature and currents, and the activities of man, such as fishing. Figures 3, A, B, and C show schematically the concept and basic components of the model, which consists of five basic groups of components. First, there are the static components--the grid net, depth of water, and type of bottom--which are prescribed and do not change during computation. Second, there is a group of components consisting of dynamic environmental factors, which are either extracted from other environmental analysis or forecasting models or computed with special subroutines in an ecosystem model. Examples are mean temperature for a given period and its anomalies, and currents caused by components such as wind and thermohaline components. Third, there is a group of a relatively large number of various biological components, which are nearly all dynamic, as is the case with living organisms in general. The model must be initialize with the best available data on standing crops of essential components such as benthos, macroplankton, and some fish by prescribing their spatial distributions and temporal variations. The best available information on trophic relationships (composition of food), feeding rates and other interspecies interactions must be introduced into the model in a time and space variable manner. Information on mobility of different components, such as seasonal migrations, must also be given as initial conditions. And finally, the sensitivity to environment or optimum environmental requirements for the various components must be prescribed in numerical form. Fourth, there is a group of components consisting of factors dependent on man, such as catch and "fishing mortality. And, fifth, one of the basic characteristics of dynamic ecosystem models is the existence of interconnected computational loops, or "feedback channels," which allow searching for iterative solutions if, when, and where changes of factors and interactions which affect the changes of other processe and quantities are introduced.

OBJECTIVES OF NUMERICAL MODELING OF A MARINE ECOSYSTEM AND THE PROSPECTIVE APPLICATIONS OF THIS MODEL

The main objectives of any numerical modeling scheme of the marine ecosystem are connected with its prospective use in solving practical as well as scientific problems (fig. 4). These objectives are: (1) Evaluation of the effects of exploitation to achieve optimum management of marine resources; (2) evaluation of the effects of environmental changes, such as climate changes, and short and medium range anomalies, on the exploitable resources and on the marine ecosystem at large, and quantitative comparison of man-made and environment-caused changes in this system; (3) reduction of all quantitative and descriptive data into easily accessible and reviewable form; and (4) determination of additional research needs and priorities.

SOME BASIC PRINCIPLES OF THE MODEL AND ITS INPUTS AND OUTPUTS

The initial formulation is essentially a time-dependent, two-dimensional model; the third dimension, i.e., depth distribution of species, temperature, and currents, etc., applies implicitly in some parts of the model. A basic, two-dimensional grid for eastern Bering Sea model (fig. 5) is an equal-area quadratic grid on a polar stereographic projection. Conversion between geographic and grid coordinates and the map factor are provided with the program in FORTRAN (appendix A).

The size of the basic grid is determined by the economy of the computer core and time requirements or availability. However, it is often necessary to look at the distributions and dynamics of a given species at a given location (e.g., on spawning grounds) in much greater detail than the relatively" coarse basic grid allows. For this purpose, a zooming technique is provided in the model, and detailed computations are carried out in fine grid inserts by special instructions for which the boundary and initial values are obtained from a large scale model and its subroutines. The fine mesh computation will also use a shorter time step than the large scale model. Figure 6 shows a hypothetical approach of a fine mesh (zoomed) computation principle and outputs of a time-dependent distribution of a species on the spawning ground as affected by a near-bottom temperature anomaly. Zoomed approaches have scientific and model-improving (tuning) as well as practical applications. They permit modeling and consequent verification of research planning of the small and mesoscale effects of environmental changes, determining the consequences of a displaced [and delayed) spawning, and formulating detailed prognostications of the location and timing of fish aggregations for use in management decisions.

To obtain realistic results, any model requires an initial extensive input of knowledge and data. This is well illustrated by Laplace, who stated, in effect, "Given the location and state of all particles in the universe and given all the forces acting upon these particles, a super-intelligence can compute all the past history and all the future of the universe." The implication is that one can start a dynamic model from an initial state (of assumed rest) and, applying the known forces, derive a dynamic state for any time period. In fact this is done with some dynamic environmental models in oceanography and meteorology. However, in an essentially biological model this type of approach (initialization) is not possible. Certain model inputs must be as accurate as possible, but other quantities and distributions can be computed, derived quantities. There is no difficulty in obtaining static input parameters for the model, such as depth; and the dynamic environmental input parameters are obtained mainly from separate environmental analysis or forecasting models. However, subroutines are provided in the ecosystem model for input of some environmental data (e.g. in form of anomalies), obtained either as observational data at a few points or as test and research modes to study the response of the ecosystem to possible changes or anomalies. This is usually accomplished with an analysis subroutine which, using first-guess field, based, for example, on time-interpolated climatology, introduces the new "observations" at specified locations into the first-guess field with a variable (determinable) smoothing coefficient. (See appendices B and C.)

The input of biological information into the model is either in the form of first-guess fields of distribution and abundance, computed from available, often fragmented, descriptions, or as dynamic variables, such as migration directions and speeds (migration routes), and aggregation and dispersal rates which are estimated from available descriptive data (e.g., from known seasonal distribution changes). The latter information, although given initially as direction and speed, is decomposed into u and v components. Furthermore, some preliminary (first-guess) decomposition is made by "movement" caused or affected by currents, movements caused by environmental properties (e.g., selection of optimum temperature by a species), and "active" movements associated with either a search for food or a spawning migration. Much of the other biological information input is given' either as time-dependent variables for a given species or group of species in the form of seasonal variation of composition of food and changes of growth rate with time or age, or as predetermined coefficients, such as feeding rates or food requirements for maintenance, and growth and optimum temperature requirements.

Several of the initially prescribed input coefficients will not remain constant during the computation, but will be made dependent variables in certain conditions with the use of restrained functions (described later), such as composition of food and feeding rates, which can become functions of food (prey) density as well as predator density. The natural mortality coefficients will also be initially estimated and introduced into the model as time and location dependent variables for a given year class, species, or group of species, which will then be changed during the course of computation.

The fishing mortality used in the model as a time and space variable input can be easily changed by the operator during the use of the model. When using the model as a decision making tool, variations in fishing mortality will determine the resultant abundance and distribution of the given species under consideration and will affect, in most cases, the statics and dynamics of the whole ecosystem.

The model outputs will be tailored to the principal use of the model, either in a research or in a decision making mode. Spatial distributions of abundance of any species can be extracted and displayed at any desired weekly or monthly time step. Furthermore, time series outputs could be taken at any given point, or the statics and dynamics of the entire stock could be summarized over the entire area of the computational grid. A simple (at this time), somewhat hypothetical example of such output is shown in figure 7, which depicts the effects of monthly fishing mortality changes on the biomass of a fish species and the effects of this change on the growth of the biomass.

THE FORMULATION (DESIGN) OF THE MODEL

Conversion of Descriptive Data and the Restrained Functions

Most biological data are available in descriptive form. However, these data are needed in numerical form for use in a dynamic numerical quantitative model. In most cases, no great difficulties are encountered in making the conversion, but there is some concern about the validity of some of the quantitative estimates. Where and when great variability in quantitative data is encountered, statistical methods will be used for deriving confidence limits or intervals. Examples of the conversion of descriptive data have been given in describing input data, such as migrations. In addition, dispersion of standing crops or species are handled with dispersion and diffusion equations and their finite difference solutions as used in numerical pollution transport and dispersion programs, with the constraint that these solutions must be conservative. The aggregation, however, must be handled with predescribed or derived movement restrained to a particular time and area. The advection equation solved and programmed by Brahm and Pedersen (fig. 8) is suitable for this purpose.

Much use must be made of "restrained functions" in an ecosystem model, which uses descriptive information converted into numerical form. These functions are not new or revolutionary, but we will make some efforts to show, name, and justify their use in condensed descriptions of widely used "programming tricks" in semi-mathematical form. The IF statement in FORTRAIN is a multipurpose, powerful tool for "solving" the restrained functions, and has been used frequently by scientists and programmers in all kinds of models and programs. Essentially, it allows the specific test of conditions and specifications for different types of formulations or changing coefficients, if and when the specified conditions are or are not fulfilled. Figure 8 gives an example of the use of restrained function for presentation and computation of temperature preference limits and effects. The general principle is that a check of temperature at the grid point at time t and t+1 is made and compared to the temperature optimum curve. If the temperature falls within the "slopes" of the tolerance curve, the fish is moved. towards the optimum temperature by changing the u or v component of the migration field in the direction of the optimum temperature in proportion to the deviation of the temperature from the prescribed optimum.

Figure 9 shows the use of restrained function for simulation of known annual vertical migrations of specified demersal species. The migration speed is prescribed with a cosine function, the time of which is affected by the phase angle κ, which can have different values at different latitudes and locations and also can be made dependent on near-bottom temperature anomalies: The midwinter and midsummer parts of the "migration speed" are restrained with a time and sign dependent check in the program.

Figure 10 shows the various conceptual and numerical approaches used to present the migrations of a given species of Pacific salmon. First, the dispersion is computed with the Monte Carlo method of Meier-Reimer. Then the migrations are prescribed as known from seasonal distribution of different age groups. The known current systems are also utilized in accelerating or decelerating the migrations. Finally the "homeward" spawning migration is computed using the same-effects of currents, but prescribing also an-active, time-dependent migration field, by which the parts of the population found well to the south in warmer water (earlier maturation) initiate the "homeward" migration.

Flow Diagrams

The complete flow diagram of a dynamic numerical ecosystem model will be long and complex. Figure 11 shows an example of a simplified annotated flow diagram of a subroutine for computation of pollock biomass dynamics. This figure indicates first the initialization of the distributions. The approximate monthly distribution of pollock in Bering Sea is derived partly from catch statistics and partly from experimental fishing results.

The annual variation of the composition of food consumed by pollock is partly prescribed with input from stomach content analysis and partly restrained at differnet grid points by knowledge of availability or abundance of preferred food items. Growth rates are from observations of weight and age relations but are also slightly restrained in the computations by using information on availability of principal food. Monthly mortality rates for given age groups are estimated from available catch statistics.

Examples of Formulas Used

It is not possible to present many formulas needed or to be used in the complex model. Figures 12 and 13 show examples of some simple types of formulas applied. The first formula (fig. 12) is an example of a modified population dynamics formula for presentation of fishing mortality. The fishing mortality coefficient is a different restrained function for each species and age group (or is time dependent when computations are made for different year classes). In addition, a time-dependent natural mortality coefficient can be computed and made a function of season and age group, if required. Fishing mortality is usually a space and time dependent input coefficient.

The second example of formulas used in the model (and given in fig. 12) is for reproduction of an annual zooplankton standing crop curve. A simplified trophodynamics formula, where food requirements for maintenance and growth are computed separately, is shown in figure 13A. The food coefficient is usually made a function of availability of food (food density), and the proportioning of food items (fig. 13B) is also made a function of relative availability of these items at each grid point and time step. The iterative balancing of food requirements and availability might lead to computation of cannibalism which occurs in many fish species. Examples of formulas used for presentation (computation) of migrations have been briefly described earlier.

The computational time step is variable throughout the model, as it is in some formulas dependent on satisfying the stability criteria (i.e. grid size and "speed" dependent), but the basic computational step can be selected with time step from a week to a month.

RELATIONS BETWEEN ECOSYSTEM MODEL, THE ENVIRONMENTAL MODEL, AND OTHER MODELS .

A schematic abbreviated listing of the relations between an ecosystem model and environmental and descriptive (conceptual) models is shown in figure 14. The environmental models provide various inputs to the ecosystem model. No feedback is provided here, as the ecosystem does not influence the statics or dynamics of the environment (except in few cases of little consequence, such as increase of turbidity due to high phytoplankton standing crop or regeneration of nutrients). The "chemo-dynamic" approach (i.e., using nutrient availability, regenerat ion, etc.) is not used in the initial state of our model, because many recent attempts in this field have not led to any useful models.

Various descriptive or conceptual models have been used to design our model and have been converted to numerical form. Future descriptive models, which provide new and more accurate knowledge, can be used to improve the model.

The conventional population dynamics models are used in modified form as parts of various subroutines. Some concepts of "energy flow" models have also been used, but in different form, i.e., in the form of the "flow" biomass. The numerous types of "water quality models" have been reviewed, but found to be too simplistic for our purpose.

Finally it should be pointed out that several possible modeling approaches might be added to the complex model and several present approaches might be modified in the course of the final designing, programming, and testing of the complete model.

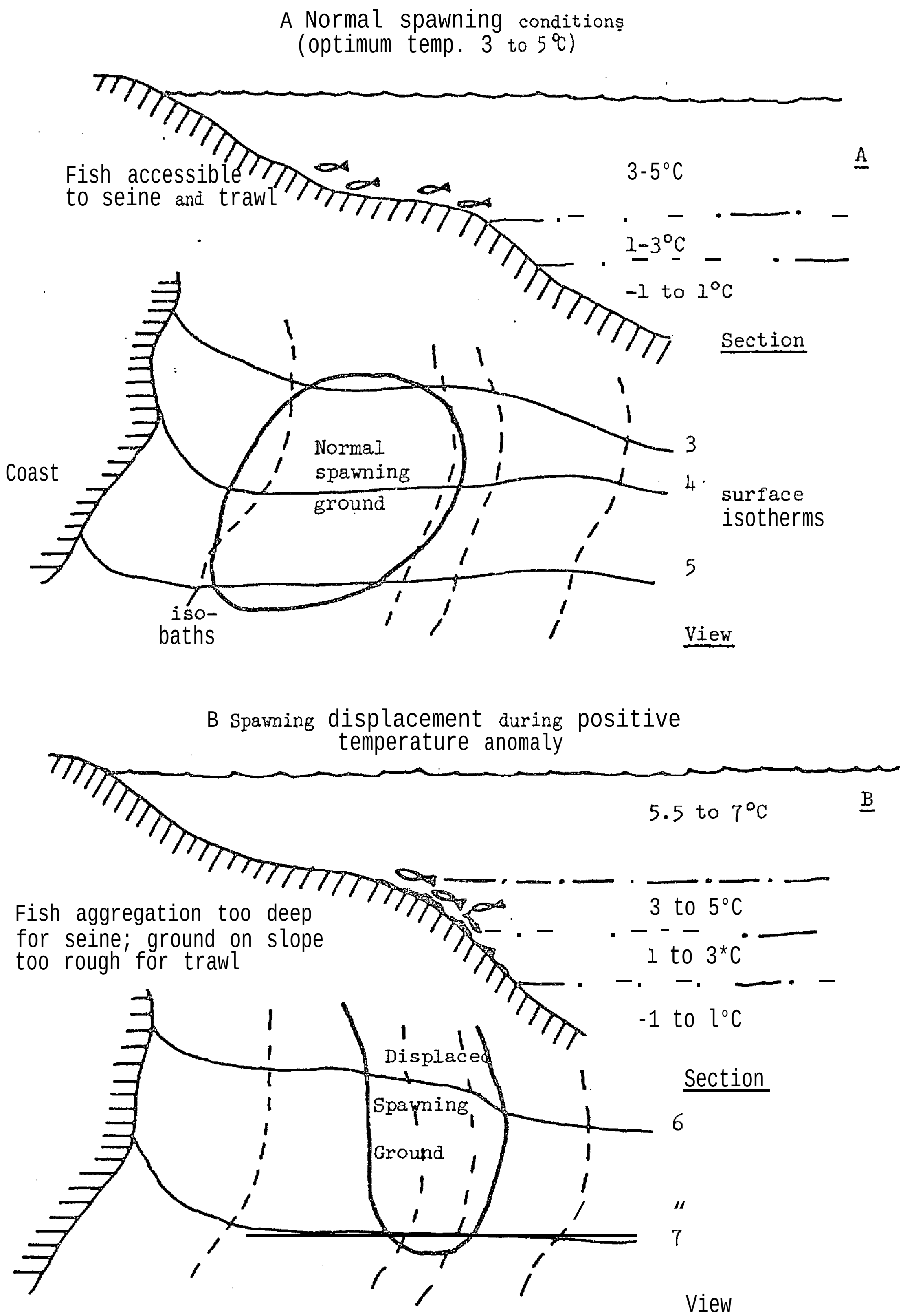


Figure 1.--Schematic example of the effect of positive temperature anomaly on cod spawning and fishing.

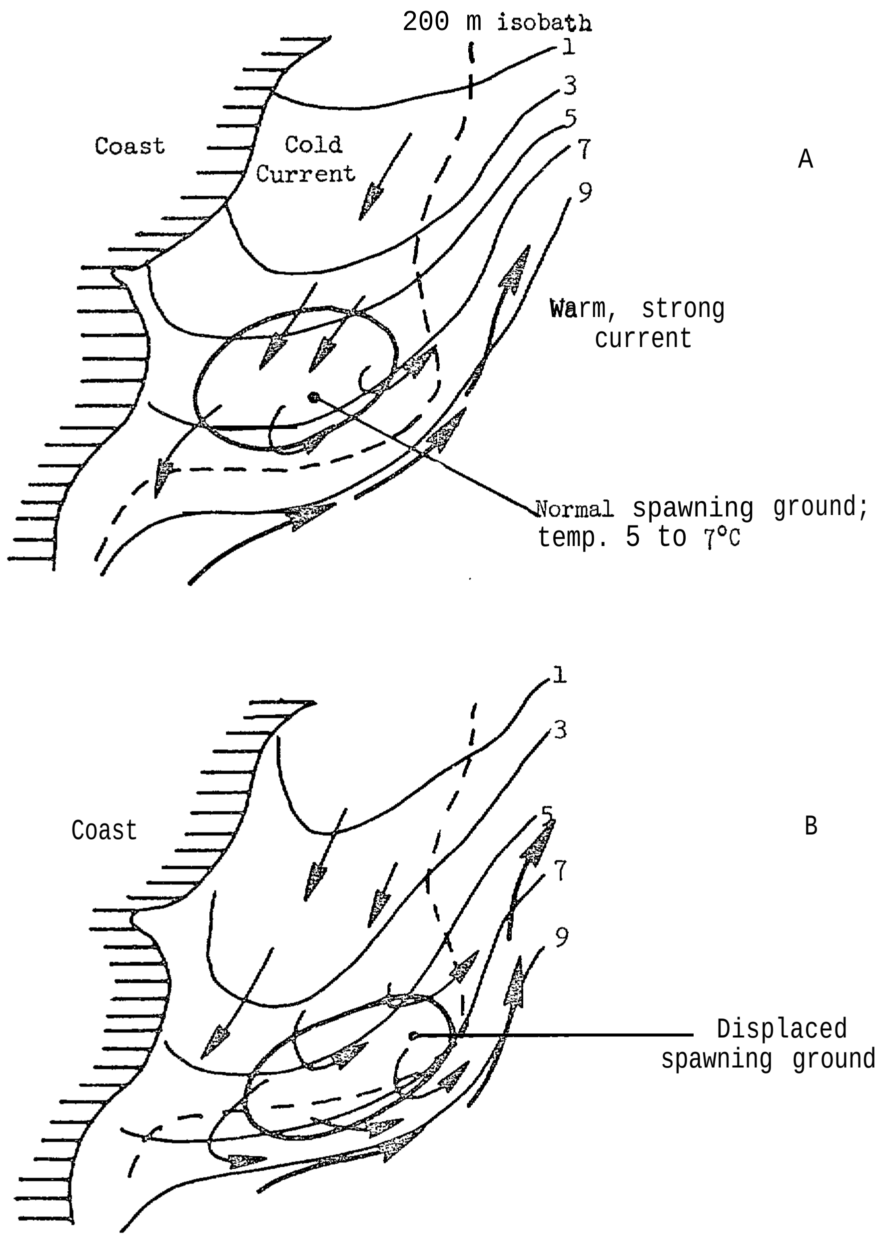


Figure 2.--Schematic example of the effect of negative temperature anomaly on haddock spawning.

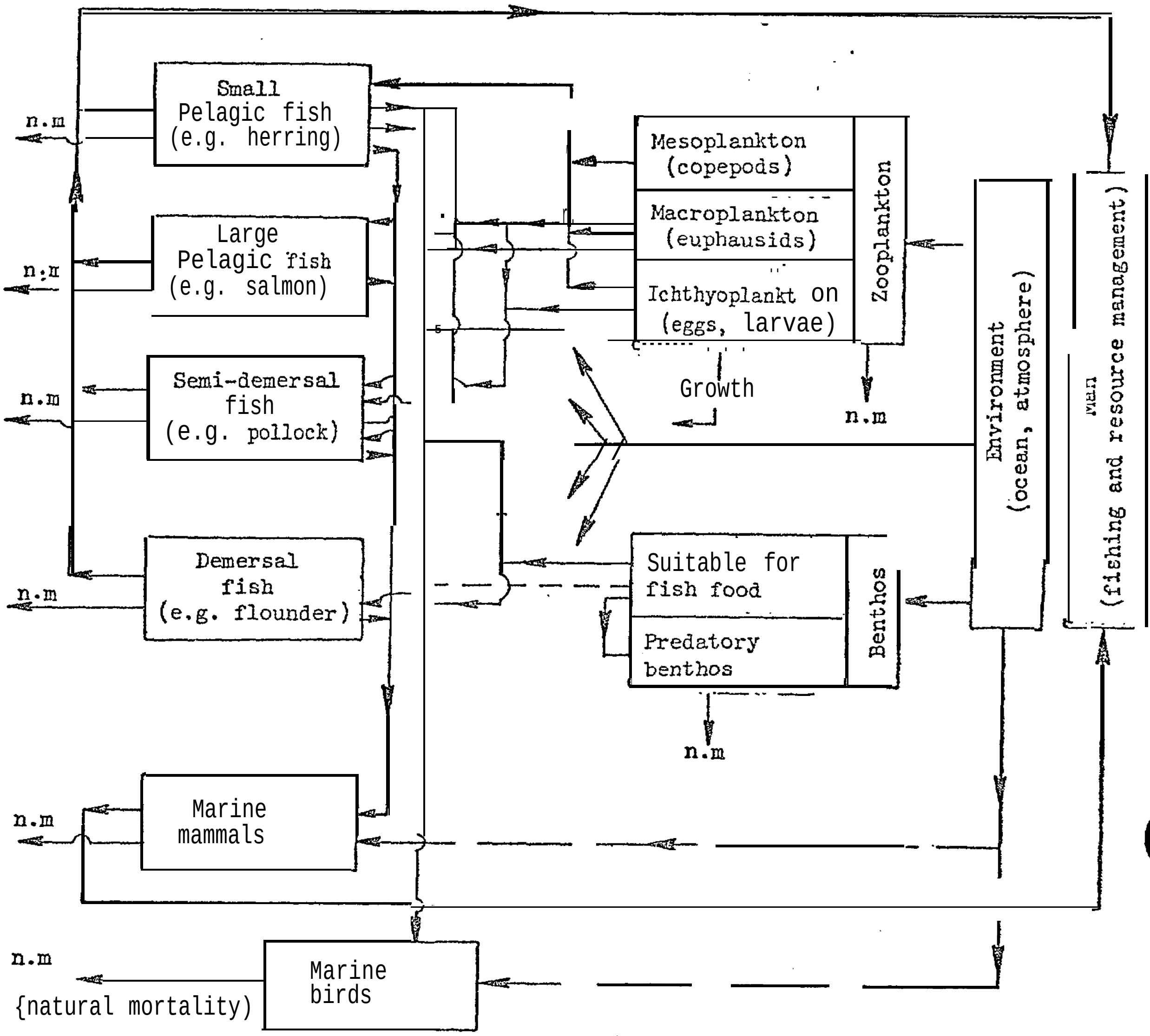


Figure 3A.--Generalized scheme of the principles of dynamic marine ecosystem model--Major Components.

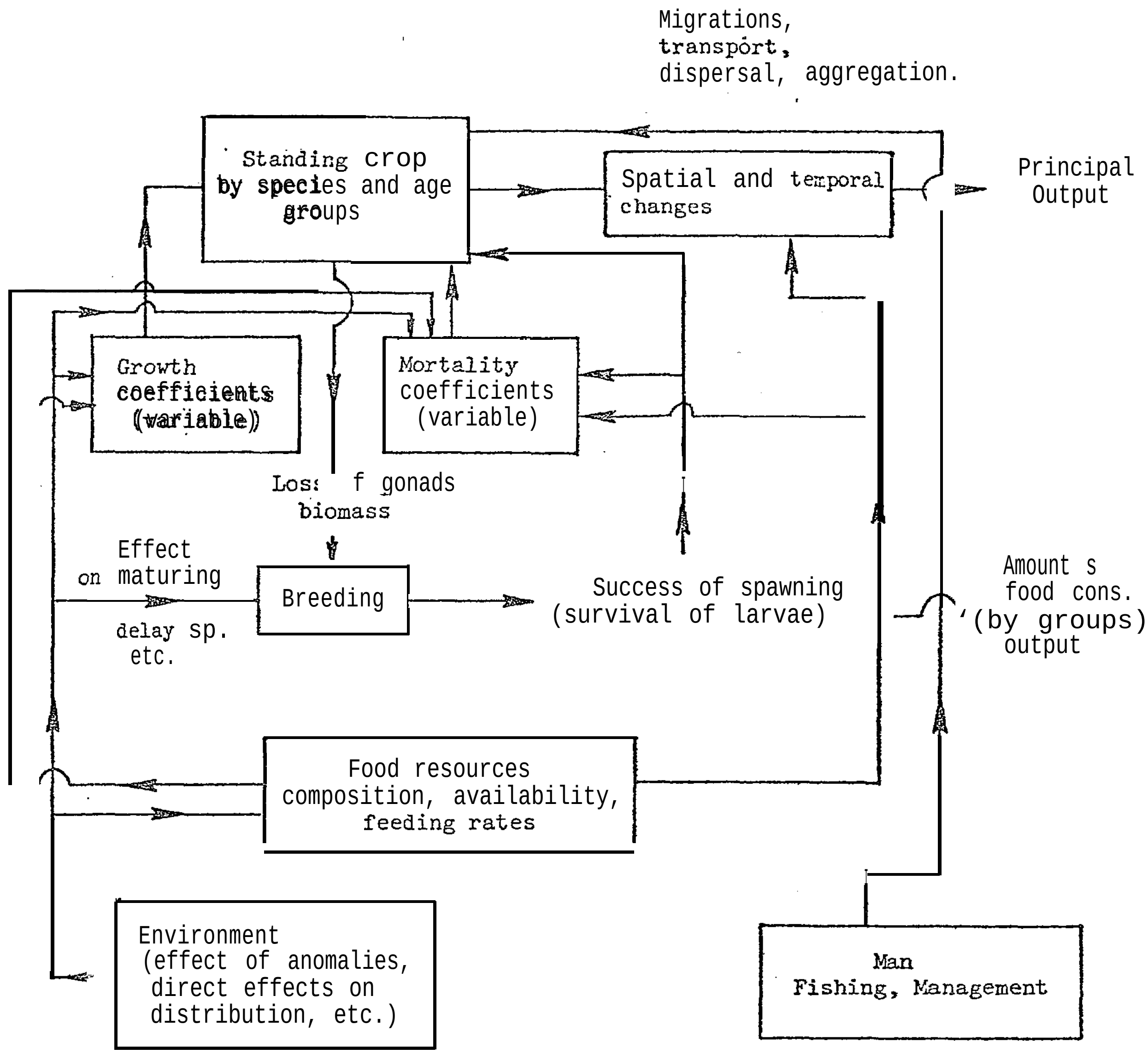


Figure 3B.--Principal processes.

I. "Open end" food web components
(inputs)

A. Zooplankton

1. Annual production, monthly mean standing crop, consumption (copepods, euphausids, decapods, etc.).

2. Proportion consumed by pollock (monthly variation, density, (availability) dependent).

B. Ichthyoplankton

As 1 and 2 in zooplankton, except 1 is dependent on spawning seasons, hatching, growth.

C. Small pelagic fish

1. Preliminary estimates of annual distribution of abundance.

2. Availability to mammals and birds.

II. Main food web components

D. Pollock

Year class composition (in terms of biomass)
Growth (by age groups)
Natural mortality (by age groups)
Fishing mortality
Food requirements for (a) maintenance, (b} growth
Food composition (by preference, age and availability)
Consumption by mammals and birds

E. Mammals (fur seal and bearded seal}

Monthly distribution and abundance
Food requirements
Composition of food
Growth
Food consumed
Kills

F. Birds (shearwaters, murres)

Monthly distribution and abundance
Food requirements
Food consumed
Effect of availability of food on mortality

1 .

Figure 3C. --Principal components of mammals, birds, and pollock submodel.

I.	Evaluation of the effects of exploitation .
11.	Evaluation of the effects of environment
III.	Reduction of data and knowledge into accessible/reviewable form
IV.	Determination of further research needs and priorities

Figure 4. --Principal objectives of the marine ecosystem model and its use.

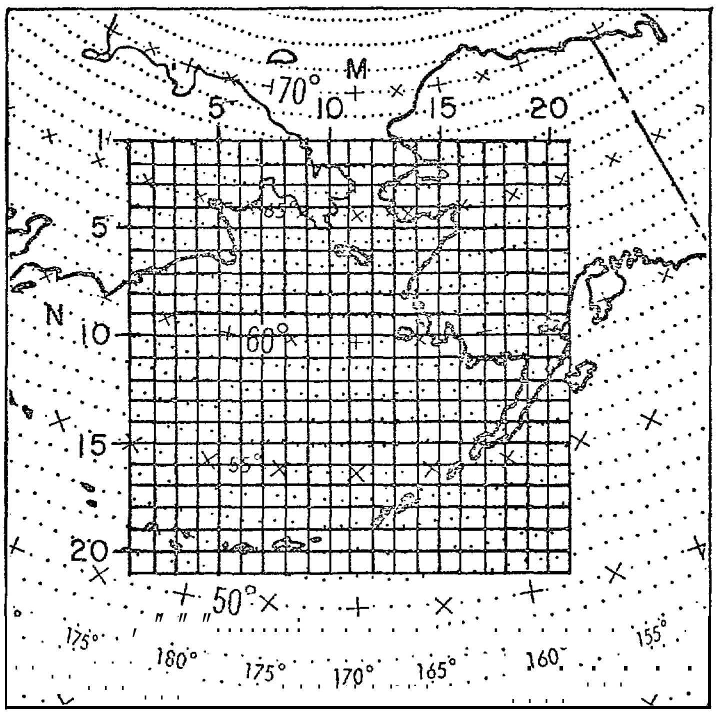


Figure 5.--Computation (model) grid for eastern Bering Sea.

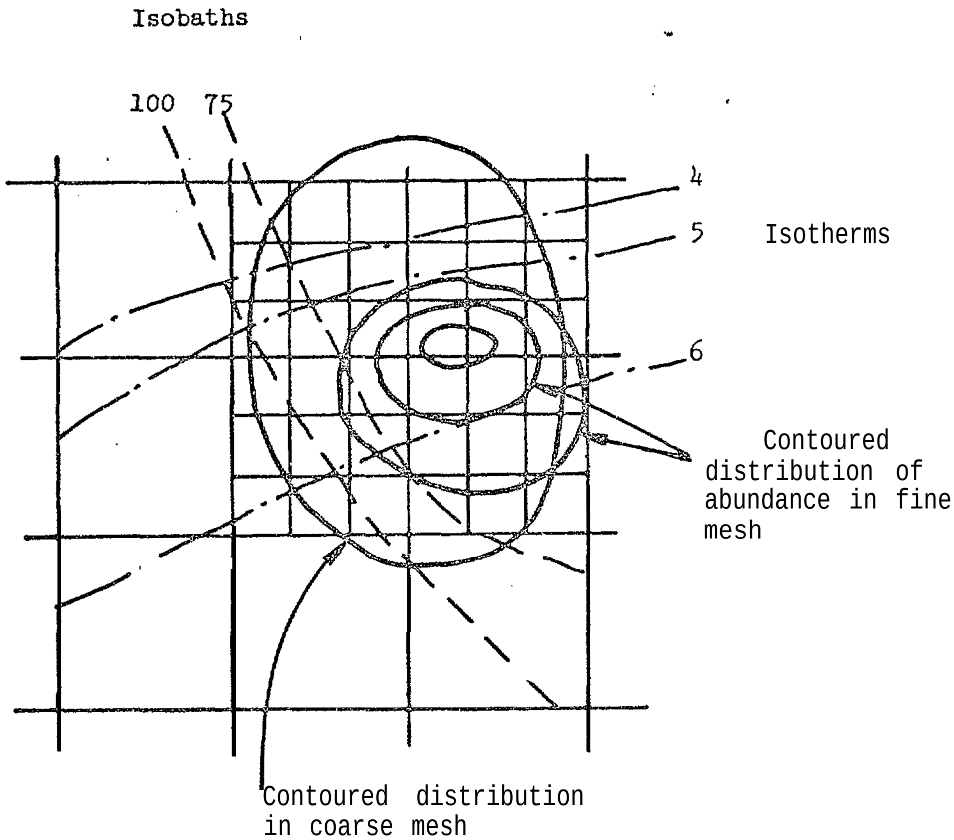


Figure 6. --Example of an inserted small-mesh (window or zoomed) model for computation of distribution and abundance on a spawning ground.

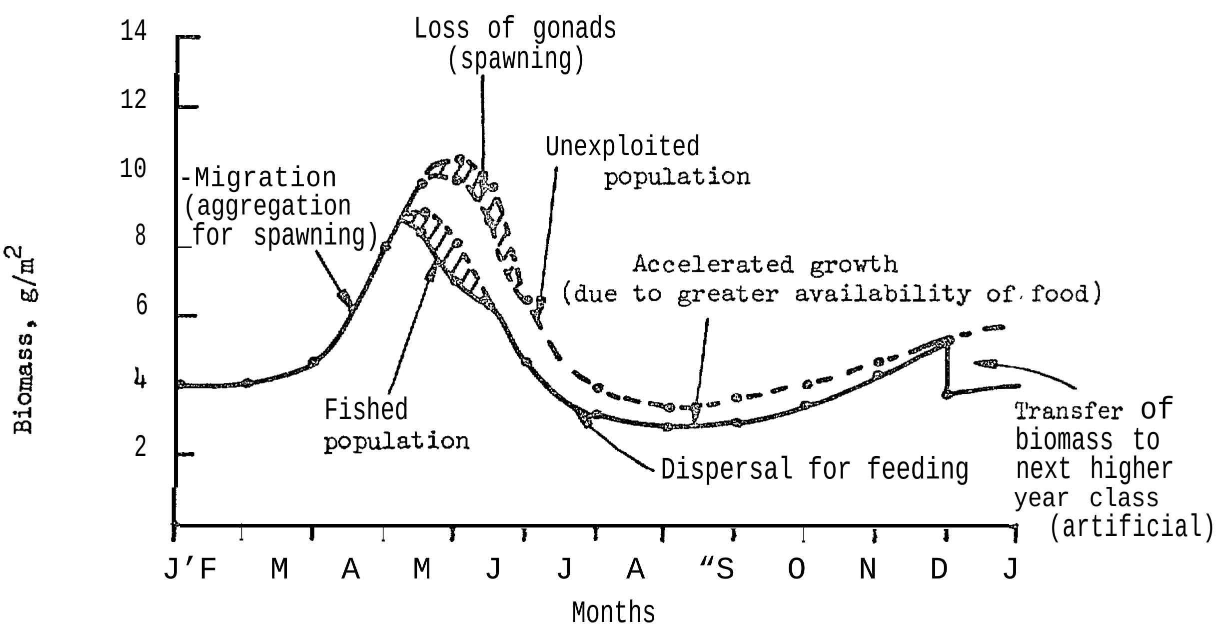


Figure 7.--Schematic diagram of a model output showing monthly biomass change of a given age group of a species at a grid point (annotated).

I. If: $T_w > T_1$ and $T_w < T_2$, then $\vec{W}_t = 0$ and $\frac{\partial B_t}{\partial t} = 0$

II. If: 'w < '1' 'r 'w > '2' 'hen

$\frac{\partial B_t}{\partial t} = - \underline{\vec{W}} \cdot \nabla B$ which in forward time, backward space, 'finite difference approximation is: $B^{t+1}_{t,m} = (1 - \sigma) B^{t}_{t,m} + \sigma B^{t}_{t,m-1}$

111. Symbols :

T_w - actual water temperature

T_1, T_2 - lower and upper limits of optimum temperature for a given species. Both can be changed annually, if this change is *known* or deduced from distribution maps:

$$T_1 = T_{1a} + T_{1c} \cos(\alpha t - \mathcal{K}_1); \quad T_2 = T_{2a} + T_{2c} \cos(\alpha t - \mathcal{K}_2)$$

T1a' '2a - the mean optimum temperature limits

T_{1c}; T_{2c} - the magnitudes of annual change

α - phase speed (30° per month)

$\mathcal{K}_1$, $\mathcal{K}_2$ - phase angles (allows e.g. narrow temp. tolerance during spawning if $\mathcal{K}_1$, and $\mathcal{K}_2$ are different).

t - time

$\vec{W}$ - emigration speed and direction (i.e. by u and v components] caused by temperature effects, function of $T_w - T_1$ and/or $T_w - T_2$ gradients.

B_t - biomass change caused by "temperature" migrations

m - grid point

σ - $\vec{W} \frac{\Delta t}{\Delta x}$, *Ax* is grid size, At is time step

Figure 8. --Example of a restrained function accounting for temperature preference.

I. $$\vec{W} = |\vec{W}_m| + |\vec{W}_c| + |\vec{W}_t|$$

$\vec{W}$ - migration speed and direction (given by u and v)

$|\vec{W}_m|$ - prescribed basic migration speed

$|\vec{W}_c|$ - currents affecting migrations

$|\vec{W}_t|$ - migration speed affected by temperature ($\vec{W}_c$ and $\vec{W}_t$ restrained in same manner as temperature preference; see Fig. 8)

II. $$|\vec{W}_m| = |\vec{W}\cos(\alpha_v t - \theta_v)|$$

Restraining tests:

1) Time, if between specified limits, no computation.

2) Time, specified for initialization of migration to (a) shallow and (b) deep water. (Migration end determined by sign change of cosine). Migration duration prescribed by α_v .

3) Depth, to determine direction of migration.

111. Example of resulting migration speed and duration:

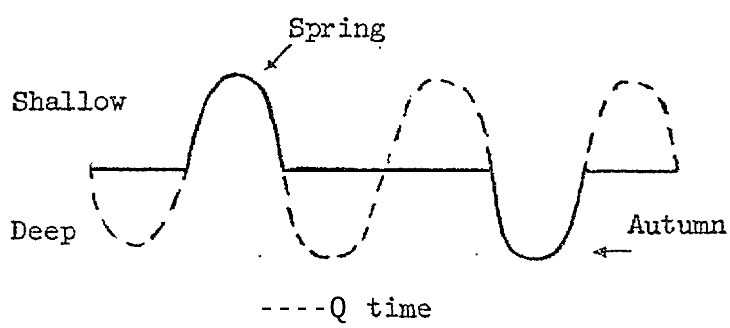


Figure 9.--Example of numerical presentation of vertical (depth) migrations of a species.

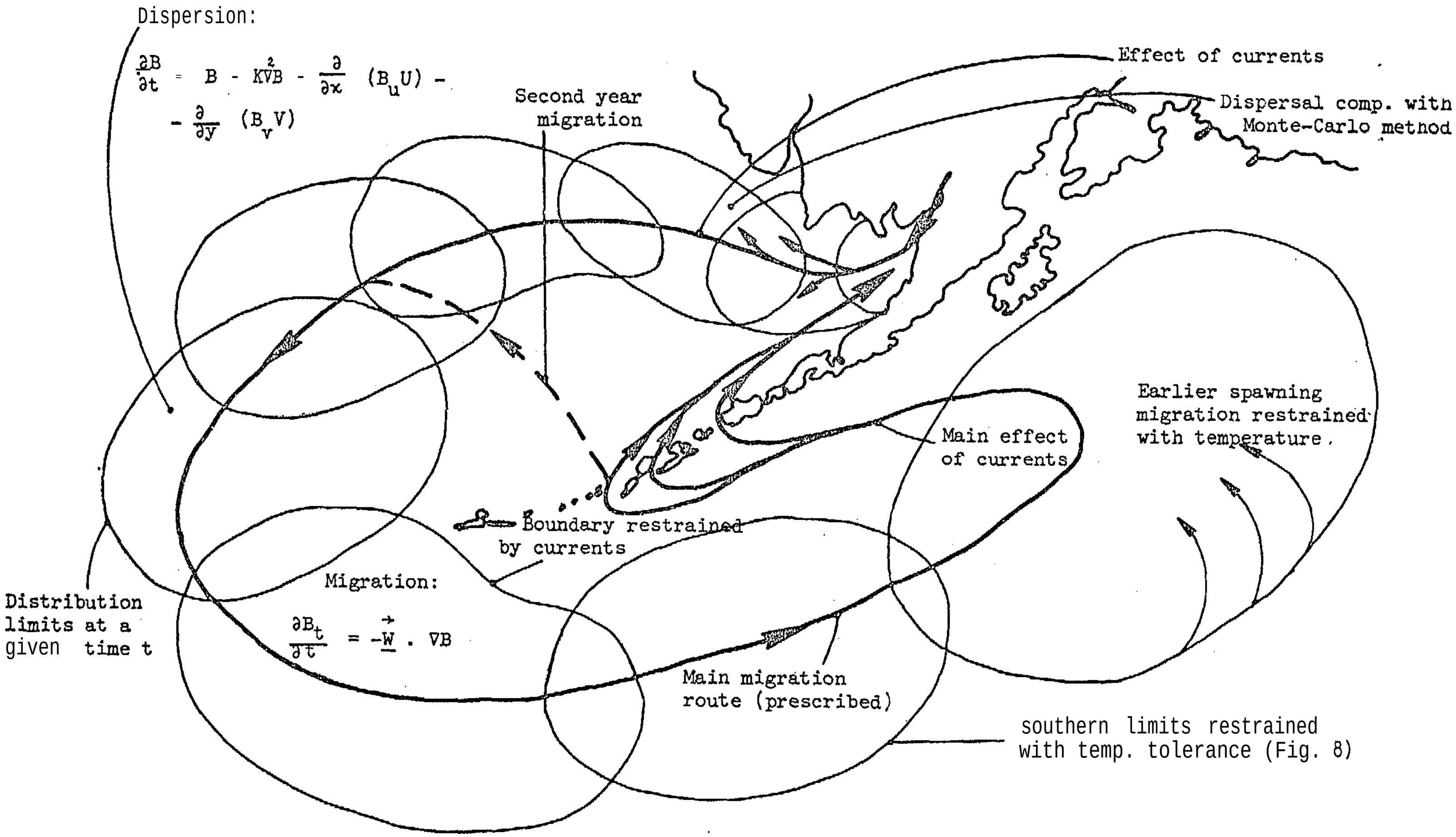


Figure 10.--Schematic diagram of computation of migrations (incl. dispersal and aggregation) of a species and indications of methods used for the solution of the migration process (exemplified by a species of Pacific salmon).

I. Initialization

A. prescribe monthly distribution of biomass by 4 age groups (juveniles, pre-fishery year-class(es), 2 fishable year-class group). (Derive data from catch statistics and experimental fishery, etc.)

B. Composition of food.

C. Generate monthly abundance of principal food groups.

D. Estimates of monthly growth, mortality, food, etc., coefficients.

II. Computation (nested DO loops)

I = 1, 12, 4

A. Growth, mortality (fishing and natural) coefficients.

B. Biomass, using A.

C. Consumption by mammals, other fish.

D. Distribution of remaining biomass (B-C) by

1. Current (juveniles only)

2. Spawning

3. Temperature preference

K = 1, 4

Food consumed (total)

M = 1, 4

Various (4) food groups consumed

Summation of outputs

Portion of biomass from each age group passing to next group

Figure il.--Generalized flow diagram of pollock subroutine.

I. Example of a conventional population dynamics formula used in the model for computation of fishing mortality.

$$B_{t,m,n} = B_{t-1,m,n}\, e^{-K_{t,m,n}}$$

$$K_{t,m,n} \rightarrow f\ (\text{fishing effort } [\text{season, location}]\text{, age})$$

II. Presentation of annual curve of zooplankton standing crop.

$$Z_{t,m,n} = Z_{o,m,n} + Z_{c,m,n} \cos(\alpha_1 t - \aleph_1) +$$

$$Z_{s,m,n} \cos(\alpha_2 t - \aleph_2)$$

$$Z_o = (Z_{max} + Z_{min})/2$$

$$Z_c + Z_s = Z_{max} - Z_{min}$$

Figure 12.--Examples of formulas used in the dynamic ecosystem model,

I. Food consumption

A. $F_{mt} = \underbrace{B_t (1-e^{-k}) g_r}_{\text{food for growth}} + \underbrace{d_m p B_t}_{\text{food for maintenance}}$

F_{mt} - monthly food consumption of a given biomass (B_t) of a given age group.

g_r - food coefficient for growth (e.g. 1:3).

p - food coefficient for maintenance

k - growth coefficient, function of age and availability of food: e.g.

$$k = k_b \left(k_p \frac{Z_{max} + P_{max}}{Z_t + P_t} \right)$$

k_b -basic growth coefficient. k_p .-proportionality factor, Z_{max}, P_{max} etc-annual maximum Standing crop of principal food items at the given location; Z_t; P_t -standing crops of food items at time t. d_m -food density dependent coefficient, similar to the expression of k above.

II. Food composition change

$Z_{cons} = A_t \times F_{mt}$

$P_{cons} = B_t \times F_{mt}$

$O_{cons} = C_t \times F_{mt}$

$B_{cons} = aO; D_{cons} = bO \quad a+b = 1$

$A_t = A_o + A_v \cos(\alpha t - \varkappa_A); B_t = B_o + B_v \cos(\alpha t - \varkappa_B)$, etc.

Z_{cons}, P_{cons}, O_{cons} - amounts of different food items consumed (e.g. zooplankton, pelagic fish, "other food").

F_{mt} - monthly food consumption of a *given* biomass.

A_t, B_t, C_t -proportions of different food items in the diet at time t.

A_o, B_o etc -annual mean of a given food item in the diet.

A_v, B_v etc -annual range of change of a given food items in the diet.

α - 30°

t - time

$\varkappa_A$, $\varkappa_B$ - phase angle

Figure 13 A & B.--Example of (I) a trophodynamics formula for food consumption and (II) annual food composition change computation.

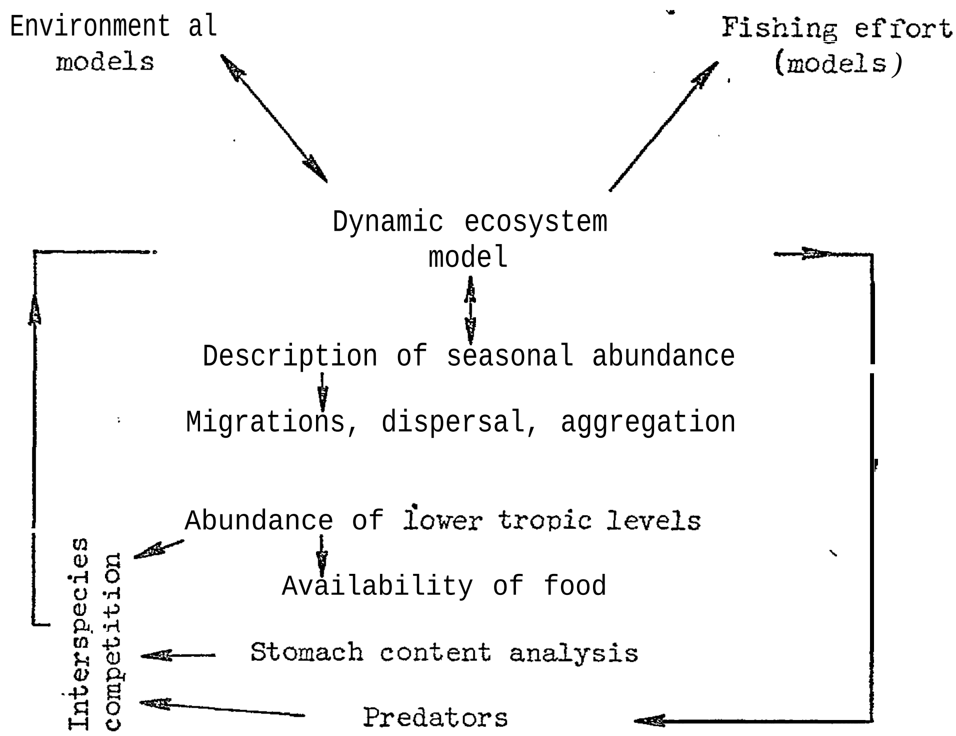


Figure 14.-'-Some relations between dynamic marine ecosystem model and conceptual (descriptive) steps in research.

APPENDIX A

The map factor *and conversion* between *grid* points and longitude/latitude.

1. Map factor (MF)

Map factor is used to correct distances' (and areas) in the polar stereographic projection [true 60°N) for any grid, using the sin ϕ (sin of' latitude) (see sin ϕ computation below).

$$\sin\phi \geq 5^\circ;\ MF = \frac{1+\sin 60^\circ}{1+\sin\phi} = \frac{1.86603}{1+\sin\phi}$$

$$\sin\phi \leq 5^\circ;\ MF = 1.86603\ .$$

2. Computation of I and J for arbitrary MxN rectangular grid if latitude and longitude are given.

(a) Using the equations for the Polar Stereographic Projection,

$$I = I_p + \frac{R_E}{d} \left| \frac{\cos\phi}{1+\sin\phi} \right| \cos(350 - \lambda)$$

$$J = J_p + \frac{R_E}{d} \left| \frac{\cos\phi}{1+\sin\phi} \right| \sin(350 - \lambda)$$

where, λ = longitude
ϕ = latitude
(I_p, J_p) = coordinates of north pole
R_E . distance from pole to equator in mesh lengths
-z-

(b) Inverse procedure computes the longitude and latitude if I and J are given:

$$\text{Long} = \lambda = k - \tan^{-1}\left[\frac{(J - J_p)}{(I - I_p)}\right]$$

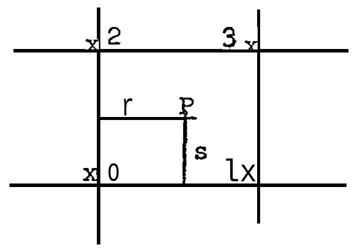
$$\text{Lat} = \phi = \sin^{-1}\left[\frac{R_E^2 - (I - I_p)^2 - (J - J_p)^2}{R_E^2 + (I - I_p)^2 + (J - J_p)^2}\right]$$

where, k = constant dependent upon quadrant
I_p = I pole
J_p = J pole
R_E = distance from pole to equator in mesh lengths (i.e. 31.205 on 63x63 grid)

APPENDIX B

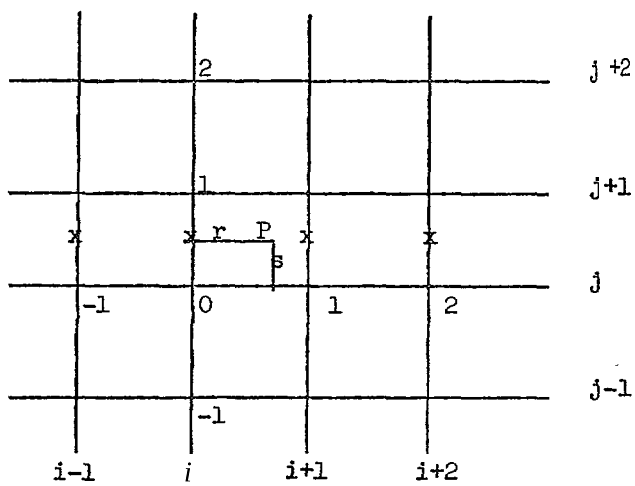
Interpolation of data fields - Method and Theory

1. If the point lies within the border zone of the MxN rectangular grid, perform a linear interpolation,



$$f_p = (1 - s)\left[(1 - r)\, f_0 + r f_1\right] + s\left[(1 - r)\, f_2 + r f_3\right]$$

2. If the point lies within the interior zone of the grid, perform a double interpolation *using* Bessel's central difference formula, with third differences.



a. Vertical interpolation is performed on columns i-1, i, i+1, and i-2 using the formula:

$$f_{I,s} = \mu f_{I,\frac{1}{2}} + \left(s-\tfrac{1}{2}\right) \Delta f_{I,\frac{1}{2}} + \frac{s(s - 1)}{2\,!}\, \mu\Delta^2 f_{I,\frac{1}{2}} + \frac{s(s-1)\left(s-\frac{1}{2}\right)}{3\,!}\, \Delta^3 f_{I,\frac{1}{2}}$$

$I = -1,0,1,2$

where,

$s \equiv$ the fractional portion of the given J.

$$\mu f_{I,\frac{1}{2}} = \frac{f_{I,1} + f_{I,0}}{2}$$

$$\Delta f_{I,\frac{1}{2}} = f_{I,1} - f_{I,0}$$

$$\mu\Delta^2 f_{I,\frac{1}{2}} = \frac{f_{I,2} - f_{I,1} + f_{I,-1} - f_{I,0}}{2}$$

$$\Delta^3 f_{I,\frac{1}{2}} = (f_{I,2} - f_{I,1}) - 2(f_{I,1} - f_{I,0}) + (f_{I,0} - f_{I,-1})$$

b. Horizontal interpolation is then performed on the interpolated row computed in a., using the formula:

$$f_P = \mu f_{\frac{1}{2},s} + (r - \tfrac{1}{2})\Delta f_{\frac{1}{2},s} + \frac{r(r-1)}{2!}\mu\Delta^2 f_{\frac{1}{2},s} + \frac{r(r-1)(r-\frac{1}{2})}{3!}\Delta^3 f_{\frac{1}{2},s}$$

where,

$r \equiv$ the fractional portion of the given I.

$$\mu f_{\frac{1}{2},s} = \frac{f_{1,s} + f_{0,s}}{2}$$

$$\Delta f_{\frac{1}{2},s} = f_{1,s} - f_{0,s}$$

$$\mu\Delta^2 f_{\frac{1}{2},s} = \frac{f_{2,s} - f_{1,s} + f_{-1,s} - f_{0,s}}{2}$$

$$\Delta^3 f_{\frac{1}{2},s} = (f_{2,s} - f_{1,s}) - 2(f_{1,s} - f_{0,s}) + (f_{0,s} - f_{-1,s})$$

APPENDIX C

Basic Flow and Equations Used in Scalar Analysis Program

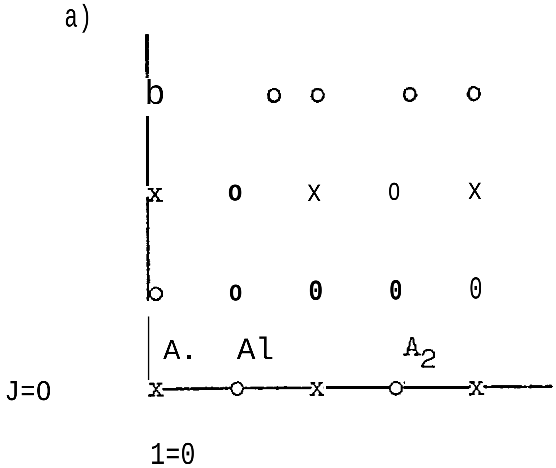
1. Pre-Analysis Section: (ANAL 1)

   a. Round i and j of observations and locate data at <u>nearest</u> grid points. Mark these points.

   b. Determine boundary: Two methods

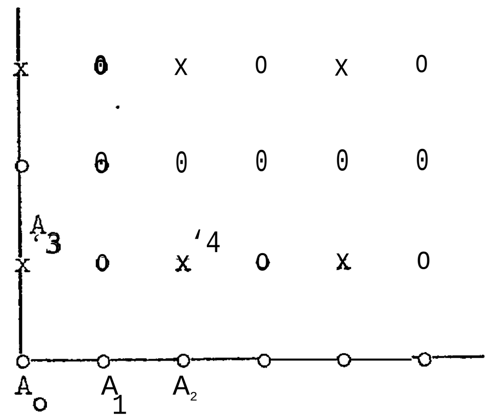
   (1) If data located at least at every other grid point in every other row and column, compute boundary values from data:

a)



$$A_1 = \frac{A_0 + A_2}{2}$$

b)



$$A_0 = A_3$$

$$A_1 = \frac{A_3 + A_4}{2}$$

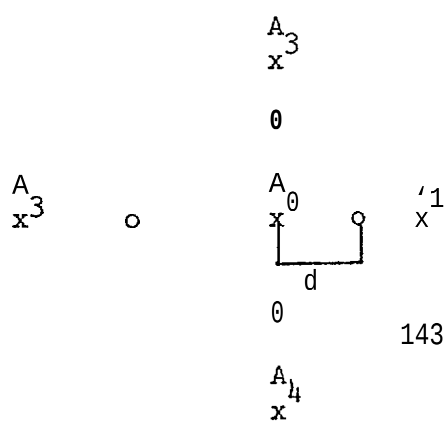
$$A_2 = A_4$$

   (2) If data random, set boundary values = a specified constant.

   c. Get $\nabla^2 A$.

   (1) If random distribution, take first guess $\nabla^2 A \equiv 0$.

   (2) If uniform distribution, get "double mesh" $\nabla^2 A$:



$$\nabla^2 A_0 \approx \frac{1}{(2d)^2}(A_1+A_2+A_3+A_4-4A_0)$$

$$= \left[\frac{1}{4}(A_1+A_2+A_3+A_4) - A_0\right]$$

d. Smooth V*A field for vorticity term:

$$\overline{\nabla^2 A_0}^{(s)} = \frac{1}{9} \sum_{k=0}^{8} \nabla^2 A_k = B$$

A_6	A_2	A_5
A_3	A_0	A_1
A_7	A_4	A_8

e. Analyze, using extrapolated Liebmann method of relaxation to solve "Poisson equation: $\nabla^2 A = B$ but holding observed values fixed.

> Note: If data distribution random, B ≡0 for first pass.

(1) Iterative step:

$A_{i,j}^{\nu+1} = A_{i,j}^{\nu} + R_{i,j}^{\nu}$, where the residual $R_{i,j}$ can be expressed as:

$$R_{i,j} = \frac{1}{4} (\nabla^2 A_{i,j} - B)$$

OR over-relaxing:

$$R_{i,j} = \frac{\lambda}{4} (\nabla^2 A_{i,j} - B) \text{ where } \lambda = 1.28$$

(2) Thus:

$$A_{i,j}^{\lambda+1} = A_{k,j}^{\nu} + .32 (\nabla^2 A_{i,j} - B)$$

(3) Continue relaxing until at $(\nu+1)$st scan,

$R_{max}^{\nu} < \epsilon$ (Here $\epsilon = 1 \times 2^{-15}$, but actual ϵ used should be data dependent.)

f. Compute new V*A

$$\nabla^2 A_{i,j} \sim A_{i+1,j} + A_{i,j+1} + A_{i-1,j} + A_{i,j-1} - 4A_{i,j}$$

g. Return to step d for 5 passes and exit after step e.

2. Main Analysis Section: (ANAL 2)

a. Compute V*A of guess field

$$\nabla^2 A_{i,j} \sim A_{i+1,j} + A_{i,j+1} + A_{i-1,j} + A_{i,j-1} - 4A_{i,j}$$

	A_2	
A_3	A_0	A_1
	A_4	

b. Smooth $\nabla^2 A$ for vorticity term.

$$B = \overline{\nabla^2 A_{i,j}}^{(s)}$$

$$= \frac{1}{5}\left(\nabla^2 A_{i,j} + \nabla^2 A_{i+1,j} + \nabla^2 A_{i,j+1} + \nabla^2 A_{i-1,j} + \nabla^2 A_{i,j-1}\right)$$

	$\nabla^2 A_2$	
$\nabla^2 A_3$	$\nabla^2 A_0$	$\nabla^2 A_1$
	$\nabla^2 A_4$	

c. Smooth the guess field

		A_6			
		A_2			
A_7	A_3	A_0	A_1	A_5	
		A_4			
		A_8			

$$A_0^{(s)} = A_0 + K\nabla^2 A_0$$

$$+ \frac{K}{2}\left(\frac{\partial^2 A_1}{\partial i^2} + \frac{\partial^2 A_2}{\partial j^2} + \frac{\partial^2 A_3}{\partial i^2} + \frac{\partial^2 A_4}{\partial j^2}\right)$$

where

$$\frac{\partial^2 A_1}{\partial i^2} \sim A_0 + A_5 - 2A_1$$

$$\frac{\partial^2 A_2}{\partial j^2} \sim A_0 + A_6 - 2A_2$$

$$\frac{\partial^2 A_3}{\partial i^2} \sim A_0 + A_7 - 2A_3$$

$$\frac{\partial^2 A_4}{\partial j^2} \sim A_0 + A_8 - 2A_4$$

$$\nabla^2 A_0 \sim (A_1 + A_3 - 2A_0) + (A_2 + A_4 - 2A_0)$$

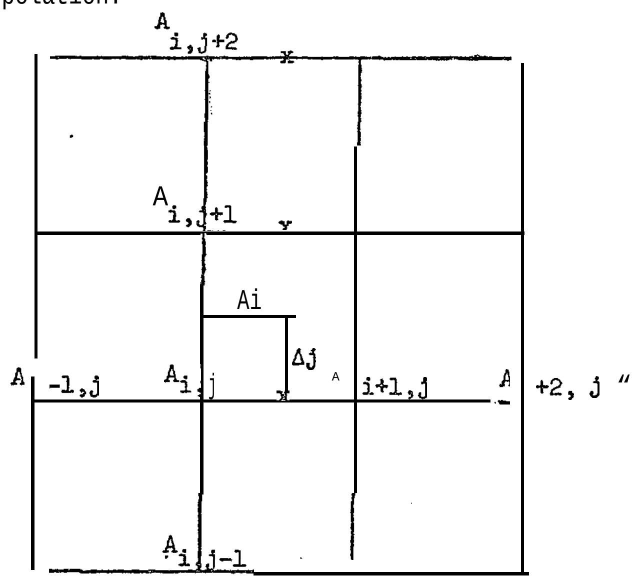
$$= A_1 + A_2 + A_3 + A_4 - 4A_0$$

and $K = \frac{1}{8}$

(1) This is a light "fixed-point" smoother which removes small irregularities but does not radically alter the grid point values.

d. Adjust the guess field with original observations:

(1) From guess, interpolate for guess value at observed i and j, using Bessel's central difference formula for a double quadratic interpolation.



(a) Four horizontal interpolations are performed first, on rows j-1, j, j+1, j+2 where (i,j) is lower left grid point, using the formula:

$$A_{i+\Delta i,j} \sim \frac{A_{i,j}+A_{i+1,j}}{2} + \left(\Delta i - \frac{1}{2}\right)\left(A_{i+1,j} - A_{i,j}\right)$$

$$+ \frac{\Delta i(\Delta i-1)}{2!}\left[\frac{(A_{i+2,j} - A_{i+1,j}) + (A_{i-1,j} - A_{i,j})}{2}\right]$$

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

$$= A_{i,j} + \Delta i\left\{(A_{i+1,j} - A_{i,j}) + \frac{\Delta i-1}{4}\left[(A_{i+2,j} - A_{i+1,j}) + (A_{i-1,j} - A_{i,j})\right]\right\}$$

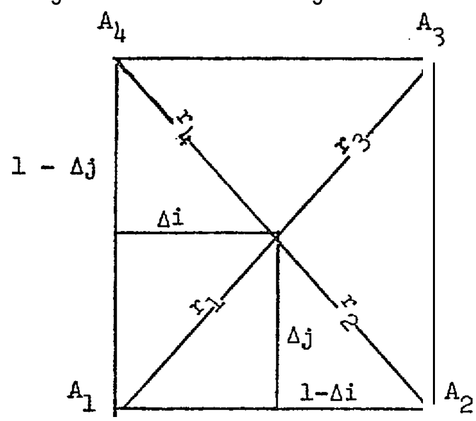
(Likewise for $A_{i+\Delta i,j-1}$: $A_{i+\Delta i,j+1}$: & $A_{i+\Delta i,j+2}$)

b. One vertical interpolation is then performed on the column $i + \Delta i$:

$$A_{i+\Delta i,\, j+\Delta j} \approx A_{i+\Delta i,\, j} + \Delta j \left\{ (A_{i+\Delta i,\, j+1} - A_{i+\Delta i,\, j}) + \frac{(\Delta j - 1)}{4} \left[(A_{i+\Delta i,\, j+2} - A_{i+\Delta i,\, j+1}) + (A_{i+\Delta i,\, j-1} - A_{i+\Delta i,\, j}) \right] \right\}$$

(2) Compute $A_{(observed)} - A_{(interpolated)}$"

(3) Compute weights for correcting each of the four surrounding grid points.



$$W_1 = \frac{1 - r_1^2}{\sum_{x=1}^{4} (1 - r_x^2)}$$

$$W_2 = \frac{1 - r_2^2}{\sum_{x=1}^{4} (1 - r_x^2)}$$

$$W_3 = \frac{1 - r_3^2}{\sum_{x=1}^{4} (1 - r_x^2)}$$

$$W_4 = \frac{1 - r_4^2}{\sum_{x=1}^{4} (1 - r_x^2)}$$

where

$$r_1^2 = \Delta i^2 + \Delta j^2$$

$$r_2^2 = (1 - \Delta i)^2 + \Delta j^2$$

$$r_3^2 = (1 - \Delta i)^2 + (1 - \Delta j)^2$$

$$r_4^2 = \Delta i^2 + (1 - \Delta j)^2$$

(4) Compute weighted difference to be added as correction to each of the four grid points surrounding the observation:

$$W_x D = W_x (A_{obs} - A_{int})$$

(5) When weights have been computed for all observations, add as correction to each grid point the "mean" of the weighted corrections resulting from each relevant observation. (A grid point is thus corrected from observations in the four surrounding grid squares.)

$$A_0(adj) = A_0 + \frac{\sum_1^k W_k D_k}{\sum_1^k W_k}$$

where K = nbr. observations affecting this grid point.

e. Analyze, holding all adjusted values fixed, using extrapolated Liebmann method of relaxation for solution of Poisson equation $\nabla^2 A = B$. See (e) under part I. Here $\epsilon = .5$ but, again, should be data dependent.

f. Return for 3 internal passes to steps c through e.

g. Return for 2 external passes to steps a through f.

h. Exit.