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9. ABSTRACT			

Mechanistic simulation models of ecological processes are becoming useful tools for the study and management of complex natural systems such as upwelling coastal regions. The goal of this cooperative project was to develop such a model, which would provide working experience with the methods and serve as a basis for future model development in Peru. This report discusses briefly the ecological assumptions and mathematical methods used in the model. The model currently runs satisfactorily, although its simple nature precludes extensive comparison with detailed, observed data. A number of suggestions for future modifications are presented. In addition, tentative, short-term and long-term programs of economic research were drawn up. The short-term programs calls for a study of artisanal fishery in order to make recommendations for the development of the fishery. The long-term program still is not clear though probably will entail economic research required for the proper development and management of the exploitation of Peru's fishery resources.

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**Ecosystems Modeling,
Economic Considerations
for a Peruvian Coastal Fishery**

James N. Kremer and Jon G. Sutinen



**International Center for
Marine Resource Development**

**University of Rhode Island
Marine Memorandum No. 39**

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Mechanistic simulation models of ecological processes are becoming useful tools for the study and management of complex natural systems such as upwelling coastal regions. The CUEA (Coastal Upwelling Ecosystem Analysis) Program in which Peruvian scientists are involved includes the development of such a simulation model as a major objective. The goal of the cooperative project between the Oceanography Division of Peru's Instituto del Mar and the Graduate School of Oceanography of the University of Rhode Island is to develop such a model, which may provide working experience with the methods and serve as a basis for future model development in Peru.

The short duration of this preliminary project meant that (1.) only a very simple model could be attempted, and (2.) it was desirable to draw heavily on the work of similar models. These included the temperate estuarine model of Narragansett Bay (Nixon and Pierce, 1970) and the upwelling model developed by John Walsh (1975). Methods of formulation and numerical methods for the ecological model were based on the Narragansett Bay model, while the ecological assumptions were in most cases very similar to those of Walsh. A physical circulation model also was developed and patterned after the general three-dimensional mixing scheme used by Walsh to simulate a simplified upwelling region.

In mechanistic modeling, the first step is to construct a simplified conceptual version of the system of interest, based on the much more detailed and elaborate understanding of the system. Thus, the extremely complex upwelling environment is characterized in reality by rapidly varying conditions, "patchiness" in chemical and biotic elements, and numerous inter- and intra-species interactions. Any of these may be included in a model if sufficient knowledge is available to allow hypothetical formulation of the basic interactions. Therefore, a certain amount of subjective judgment is required to specify what properties of the real system are to be treated in the model system. These decisions are usually based on the probable importance of the processes in the system as perceived by the researcher, although the personal interest of the investigator is, of course, another valid criterion. In addition, the decision is not final, and a simple preliminary model can and should be continuously modified--explaining areas proving to be of greater interest, and perhaps simplifying those where less detail seems needed. The present modeling effort is necessarily preliminary, and future work by Instituto del Mar personnel may mean that feedback from such theoretical analyses will affect practical and experimental research.

The simplified conceptual model of the upwelling region is represented in figure 1. Radiation, temperature and physical circulation are external forces operating on the biological community. Phytoplankton, the primary producers, are of basic interest in this first version of the model, and a fair degree of physiological detail is represented in their compartment. But the response of the phytoplankton cannot be adequately represented apart from other biotic influences, such as grazing and excretion by herbivores. Thus these interactions are included in the model, albeit very crudely and simply. The logical path for future work to take is to expand the detail in these compartments and provide mechanistic formulations for such processes as ingestion, respiration, reproduction and growth.

The phytoplankton compartment of the present model includes mathematical formulations of growth and nutrient uptake as a function of temperature, ambient nutrient concentrations, and light. The approach taken here characterizes the complex, multi-factoral nature of the growth process by postulating a temperature-dependent maximum rate for otherwise optimum conditions. This maximum is then reduced by terms representing the extent to which nutrients (nitrogen, phosphorous and silica) and light are less than optimum. The predicted net rate of production is then the product of these three terms. The realized growth, or net community primary production, depends on the predicted growth rate as diminished by herbivore grazing. Nutrient uptake is commensurate with predicted growth, while herbivore excretion and physical upwelling supply nutrients to the system. The physical circulation is modeled in a simple way which is, however, flexible enough to allow various rates of transport and velocity gradients to be approximated in the model region.

The following report is a brief discussion of the ecological assumptions and the mathematical methods used in the model. Throughout this discussion, frequent reference is made to the model of John Walsh (1975). His section headings are used, and references to pages in his report (wp-) are made to facilitate the comparison. All citations to the work of Walsh refer to this paper unless otherwise specified.

The model presently runs satisfactorily, although its simple nature precludes extensive comparison with detailed, observed data. A number of suggestions for future modifications are presented, and it is hoped that they will provide immediate direction for continued modeling efforts at the Instituto del Mar. Nevertheless, even this primitive model has begun to play a role in suggesting relevant questions, pointing out uncertainties in our present knowledge and assisting in the planning of future research.

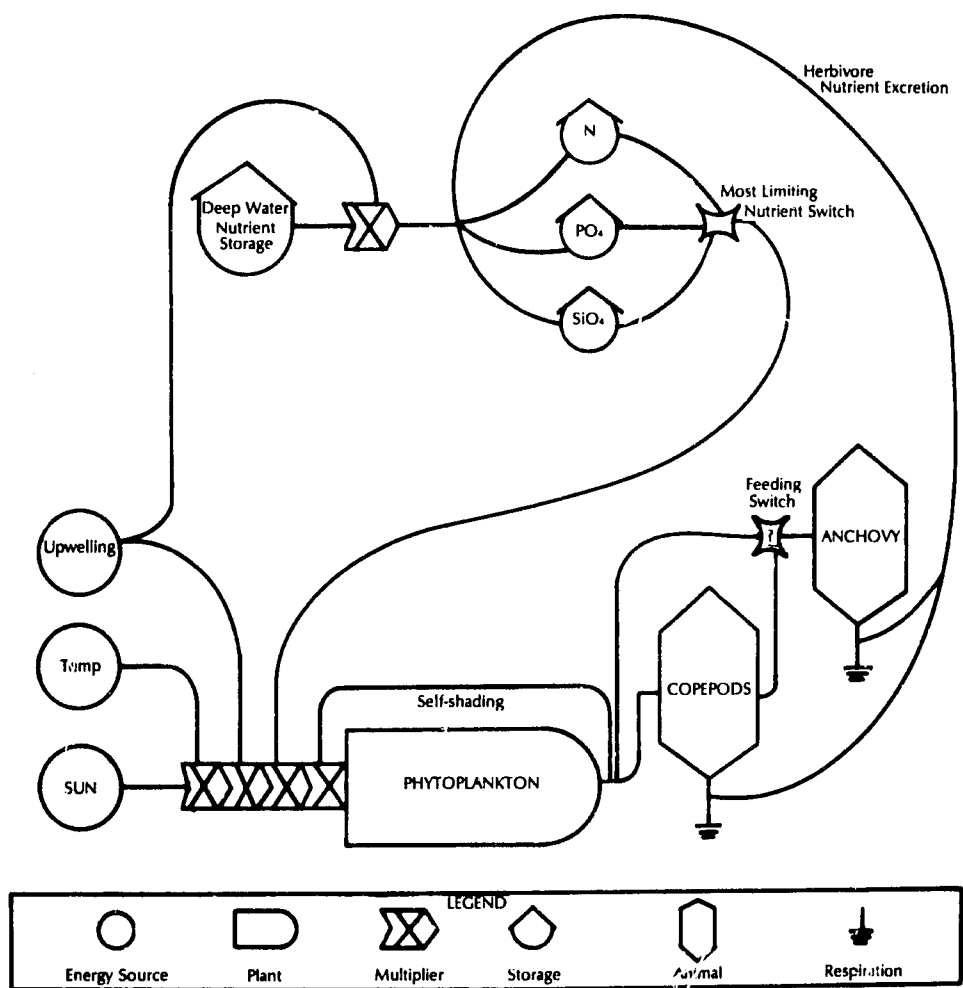


Figure 1.

FORMULATIONS

Physical Assumptions

Circulation--general. The physical circulation model "UPWELL" was written to be as similar as possible to the mixing model of Walsh. Basic differential equations including advective and turbulent mixing in three dimensions and biological changes are solved, using a simple forward finite-difference method. Two different velocity fields were chosen which are like Walsh's (Wp 209), with the slow upwelling simulated by velocities identical to his figure 7, and fast upwelling simulated by doubling these. While the general UPWELL model is for any three-dimensional region (10 x 10 x 10 grids) and any velocity field, biological applications were completed using a simple version with fewer computation cubes: a one-dimensional region, 100 kilometers offshore x 70 meters deep. Apparently Walsh used a spatial region of these same dimensions in his ecological model, rather than the more complete three-dimensional model.

Diffusion. The equations chosen by Walsh for advection (Wp 218) and for turbulent diffusion (Wp 218) were used in this model with the same parameter values for the constants. Some uncertainty exists about whether or not Walsh used both equations explicitly, or whether diffusion was ignored by assuming it was "implicitly" included in the advection equation.

Boundary Conditions. The assumption made by Walsh--that air and coast boundaries should use concentrations of zero--violates the assumption that no diffusion may occur through these boundaries. A different assumption was made in this model which assures no gradient of concentration at the boundaries. Therefore, all concentrations at the boundary are made equal to the value at first adjacent cube.

Radiant Energy. A constant value of radiation of 300 langleyes per day was used in all cases for the ecological model. The ability of the plants to acclimate the light of optimal photosynthesis makes the exact choice of the radiation less critical. Only the relative values of the light-to-optimum ratio is important in the model.

The incident light follows the common exponential decrease

$$I_z = I_0 e^{-kz}$$

where I is radiation (ly/time) at surface (I_0) or at depth z (I_z).

The extinction coefficient (k) is calculated using the equation

$$k = k_0 + 0.2514 P + 0.5047 P^{0.66667}$$

where P = mg phytoplankton C/L. This is identical to the original equation of Riley (1956) for a ratio of phytoplankton C:Chl = 35. The same equation was used by Walsh but with P in units of nitrogen.

A ratio equal to 35 was chosen based on a preliminary review of data in reports of *Anton Bruun* cruises, but should be verified or changed by more complete analysis by the staff at the Instituto.

The value of $k_0 = 0.025$ (extinction coefficient of water due to non-chlorophyll materials also is based on *Anton Bruun* data. A preliminary look at six samples by plotting observed k vs. $\text{Chl } a$ suggested an intercept ($\text{Chl} = 0$) of about 0.025. This too should be verified or altered by future work.

Chemical Assumptions

Nutrient Regeneration. While the main source of nutrients is probably the rich upwelled water, the role of nutrients regenerated by zooplankton or anchovy excretion may also be important. In this model, as in Walsh's, excretion of ammonia, phosphorous and silicate by the herbivores takes place in the ratio N:Si:P of 11:0.5:1 for zooplankton and 5:0.22:1 for anchovy. Walsh assumed that excretion only occurs when the animals are feeding. While this may be an uncertain assumption, my results suggest that without it the contribution of nutrients becomes much more important than it should. It seems that the assumption is necessary, and the interpretation is useful, that it is an attempt to simulate the patchiness of the animals' distribution.

Nutrient Uptake. Within the PHYTO submodel, one nutrient is chosen as most limiting each hour of the simulation. The basis for this selection is different than Walsh's, since there appear to be difficulties with his method. Both methods have been tried in this model, and the simulation results are very interesting. Some valuable experiments are suggested by the disagreement of the methods, and perhaps in the future the Instituto staff will be able to complete the experiments thus providing some answers to the questions.

Walsh chooses to select the "most limiting" nutrient on the basis of a comparison of nutrient ratios in the water with the ratios required by the phytoplankton. This nutrient is then used in a kinetic calculation of growth (or uptake) using the familiar Michaelis-Menton equation:

$$\text{Uptake} = U_{\max} \cdot [N] / (K_s + [N]) \quad (\text{Wp 212})$$

In this report's model, the kinetic calculation is made for all three nutrients, and the "most limiting" is chosen on the basis of this comparison; that is, the nutrient that is most difficult for the plant to take up from the water is selected as most limiting.

The two methods are very different primarily because the values of the half-saturation constants (K_s) have ratios that are very different from the requirements of the plants. The plants require

nutrients in the ratio N:Si:P of 16:10:1, but the K_s constants used in the model have the ratio 6:3:1. Therefore it is possible--and in fact it frequently happens in the model simulations--that nitrogen or silica are in concentrations which are lower than the ratio in the phytoplankton, while the kinetic calculation indicates that phosphorous is much more difficult for the plant to take up, and therefore should probably be considered limiting.

The difference is a theoretical one. Walsh's is an assumption based on the standing-stock of nutrients. The alternative is a dynamic assumption, based on the physiological capabilities of the phytoplankton cells. However, the implications are important; Walsh predicts that nitrogen and/or silica are limiting while the kinetic calculations clearly show phosphorous to be limiting. Experiments that would be helpful to resolve this question include two.

1. Nutrient kinetic observations should be made to more accurately evaluate the value of the K_s constants that are appropriate for the species in the upwelling environment. For example, measurements of growth observed at different concentrations should show a hyperbola that agrees with the Michaelis-Menton theory.

2. Enrichment experiments should be conducted where natural populations are grown in freshly collected water to which different materials have been added. If nitrogen or silica is limiting, addition of these chemicals should stimulate growth, while the addition of phosphorous alone will not. Such experiments as these would add to a basic understanding of which controls are important in the growth of phytoplankton populations in upwelling areas.

Inhibition. In this model, the preference of phytoplankton for ammonia before nitrate is included in a very simple form. Rather than a gradual transition as in the equation used by Walsh (Wp 212) the phytoplankton use ammonia until there is no more. Any additional nitrogen is provided by the concentrations of nitrite and nitrate in the water.

Biological Assumptions

Phytoplankton. In the present preliminary form of the model, the rates of all processes are assumed to represent averages over 24 hours. No diel periodicity is now included, although the calculations are made on an hourly time-step (dt=one hour) for the circulation requirements. It would of course be desirable to include daily patterns for many processes, and this would be a good direction for future work on the model to take.

The maximum possible growth of the phytoplankton (G_{\max}) in the model is determined using the general equation of Eppley (1972). He has demonstrated that a strong upper limit appears to exist as a function of temperature. The equation has the familiar form of an exponential relation:

$$G_{\max} = e^{(0.063 \text{ Temp} - 0.16)}$$

The remaining parts of the PHYTO submodel estimate to what extent light and nutrients limit the ability of the plants to achieve this maximum growth. Two fractions are calculated which represent the limitations, LTLIM and MXLIM.

The limitation of less than optimum light levels (LTLIM) is based on a formulation by DiToro et al. (1971) which represents a double integration of the physiological response equation suggested by John Steele (1962):

$$G = G_{\max} \frac{I_0}{I_{\text{opt}}} e^{(1 - \frac{I}{I_{\text{opt}}})}$$

DiToro has shown that the integral of this equation, when considered over the total daylight period and the depth of the water (or mixed layer), is possible if the assumption is made that radiation is constant throughout the day. My work at the University of Rhode Island (Nixon and Kremer, in press) has suggested a correction factor of 0.85 should be applied when noonday inhibition at the surface is considered. This correction is used in this model only in the surface layers when the radiation exceeds the optimum for photosynthesis.

The exact value of I_0 , the optimum value for photosynthesis, is chosen to be 50 percent of the surface. While this choice is arbitrary, it is well supported by observations of Steele (1962) and others, and may be assumed to represent the acclimation of the plants to the changing seasonal light intensity. Walsh makes a similar assumption, choosing a "half-saturation" constant for light of 10 percent of the surface value. Although Walsh includes diel variation, he ignores some aspects of the basic photosynthesis-light response which may affect production at the surface quite dramatically. In addition, he chooses to consider light and the nutrients together, so that only one of them is limiting growth at any depth and time. This model, however, considers a 24-hour average, and light effects are considered in addition to nutrient limitations. In the future, it would be desirable if diel variations could be added to the model, since the hourly time-step is already necessary for the circulation computations. In the phytoplankton formulation, this would mean that the original equation of Steele (for the instantaneous rate) should be used each hour and at every depth, with surface radiation following a curve from dawn to noon to dusk.

The basis for the nutrient formulation has already been described, and only a brief mention of it is necessary here. Half-saturation constants (identical to those of Walsh) were chosen to be used in Michaelis-Menton equations. Three values are calculated, one for each of the nutrients, NLIM, PLIM and SILIM. The smallest of these numbers represents the most limiting nutrient, and is used in the growth prediction. A form of the equation is used which gives a unitless fraction:

$$NLIM = G/G_{\max} = [N]/(K_s + [N])$$

MXLIM, the most limiting fraction, is simply the minimum of NLIM, PLIM, and SILIM.

The final predicted growth rate is:

$$GP = G_{\max} \times LTLIM \times MXLIM \quad (\text{day}^{-1})$$

The actual growth is determined in an exponential rate equation

$$P = P_0 e^{(GP - \text{grazing}) \cdot \text{time}} \quad \text{biomass (mg C/L)}$$

Herbivores. In this model, grazing and excretion by the herbivores are treated very simply. Rates for the two processes are chosen from the data presented by Walsh, and biomasses were selected, also directly from Walsh. No diel vertical migration is considered for either the zooplankton or the fish. Instead, all rates are averaged over the total water column and over 24 hours.

Biomass Estimates--Zooplankton. Walsh suggests a biomass of 41 mg dw/m³ during the autumn characterized by relatively slow upwelling. During the winter when upwelling is faster, the biomass is more dispersed (12 mg dw/m³). Since the unit of volume in the biological model is liters, the estimates are converted:

$$\begin{aligned} \text{Autumn: } & 41(\text{mg dw})/\text{m}^3 \times 0.001 (\text{m}^3/\text{L}) = 0.041 (\text{mg dw/L}) \quad (24 \text{ hr. avg.}) \\ \text{Winter: } & 12 \quad \times 0.001 \quad = 0.012 \end{aligned}$$

Biomass Estimates--Anchovy. The same calculation may be made for the estimate of fish biomass used by Walsh:

$$\begin{aligned} \text{Autumn: } & (6 \text{ fish}/\text{m}^3) \times 0.001 = (0.006 \text{ fish/L}) \quad (24 \text{ hr. avg.}) \\ \text{Winter: } & 0.04 \times 0.001 = 0.00004 \end{aligned}$$

Grazing Stress. Grazing Rate Estimates--Zooplankton. Walsh cites literature relating growth and assimilation to ingestion which allows the following budget:

$$\text{Growth} = \text{assimilation} - \text{excretion} \quad (\text{Wp 216})$$

$$0.268 I_z = 0.6 I_z - 0.03 (\mu\text{g-at N})/(\text{mg dw hr})$$

where I_z = ingestion of zooplankton. Solving this for ingestion:

$$I_z = 0.0903 (\mu\text{g-at N})/(\text{mg dw hr}) \text{ ingested}$$

But the food that is ingested (phytoplankton) has the composition 106 carbon:16 nitrogen. Or

$$0.0795 \text{ mg C}/\mu\text{g-at N}$$

Then the ingestion may be converted to carbon:

$$I_z = 0.0903 \times 0.0795 = 0.007 (\text{mg Phyto. Carbon})/(\text{mg dw Zoo hr})$$

ingested. This is the same as Walsh's rate of 0.02 hour^{-1} (Wp 216)

Grazing Rate Estimates--Anchovy. The fish ingestion is estimated in the same way for two seasons:

$$\text{Growth} = \text{assimilation} - \text{excretion}$$

$$94.2 (\mu\text{g-at N})/(\text{fish day}) = 0.8 I_A - (486 \mu\text{g-at N})/(\text{fish day}) \quad (\text{Wp 215})$$

$$I_A = 725.3 (\mu\text{g-at N})/(\text{fish day}) \text{ or } 30.2 (\mu\text{g-at N})/(\text{fish hr}) \quad (\text{autumn biomass})$$

$$I_A = 1180 \text{ or } 49.2 (\text{winter biomass})$$

Again, the ingested phytoplankton ratio is 106:16, and the carbon ration may be calculated:

$$I_A = 30.2 \times 0.0795 = 2.4 (\text{mg Phyto Carbon})/(\text{fish hr}) \text{ ingested} \quad (\text{autumn})$$

$$I_A = 49.2 \times 0.0795 = 3.9 (\text{winter})$$

The rate of 2.4 is almost the same as Walsh's rate of 0.005 hour^{-1} (Wp 215)

Excretion Rate Estimates. Zooplankton. Walsh cites McCarthy (1971, see Wp 215) for the estimate of 0.03 ug-at NH_3 /(mg dw·hr). The ratio of nutrients excreted was chosen to be N:Si:P 11:0.5:1 (Wp 211). Thus, the hourly excretion rates for zooplankton are:

$$\begin{aligned}\text{EXCN}_z &= 0.03 \text{ ug-at (mg dw hr)} \\ \text{EXCP}_z &= 0.0027 = \text{EXCN} \times (1 \text{ ug-at P})/(11 \text{ ug-at N}) \\ \text{EXCSI}_z &= 0.0013 = \text{EXCP} \times (0.5 \text{ ug-at Si})/(\text{ug-at P})\end{aligned}$$

Anchovy. The same estimates are made for the fish excretion using the ammonia excretion rate of 13.5 ug-at N/(g dw hr) and a ratio N:Si:P of 5:0.22:1 (Wp 215 and 211). To convert the estimates to rates-per-fish, a value for weight of each fish is required. Estimates of 1.5 grams (dry weight) per fish (autumn) and 2.5 grams (dry weight) per fish (winter) are based on the wet weight values of 6.5 and 10.5 given in Wp and the conversion of 25 percent of wet weight given in Wp 215. The excretion rates then are calculated:

$$\text{EXCN}_A = (\text{ug-at N})/(\text{g dw hr}) \times 1.5 \text{ (g dw)}/(\text{fish}) = 20. (\text{ug-at N})/(\text{fish hr})$$

EXCP_A and EXCSI_A are calculated in the model similarly using the ratio of excreted nutrients and the appropriate biomass for the season.

Grazing Threshold. A more traditional grazing equation than that used by Walsh is used in this model to express food density dependence. Ivlev's equation (1945) has frequently been used for density dependence in grazing models:

$$\text{Ration} = R_{\max} (1. - e^{-k(P-P_0)})$$

or

$$\text{XLIM} = R/R_{\max} = 1. - e^{-k(P-P_0)}$$

Walsh used the same rectangular hyperbola equation he uses for nutrients and light:

$$R/R_{\max} = (P - P_0)/[K_s + (P - P_0)]$$

The two equations are similar at low food densities, but at the higher concentrations, Walsh's ration is significantly lower than Ivlev's. The distinction is arbitrary however, and either should be equally satisfactory (see Mullin et al. 1975).

Grazing thresholds are somewhat controversial (Frost 1975). While it seems reasonable that there should be such a threshold, for zooplankton at least, the experimental data do not always support the assumption. In simulation models, thresholds may avoid the mathematical artifact of over-

grazing--when the predicted ration consumes more than the available phytoplankton, often forcing the concentration to go below zero. The mathematical method of solution used in this model, which will be discussed in more detail later, also avoids the artifact problem, so the threshold was not considered necessary. The additional interpretation given by Walsh is that the threshold simulates patchiness. Thus, when phytoplankton concentrations are below the threshold, he assumes that no herbivores will be in the region. This is perhaps more reasonable for the motile anchovy than the zooplankton, but it is nevertheless an interesting suggestion. Thresholds were used in the model, though not well established, so that their effect may be evaluated.

The calculation of excretion and grazing in this model results from the biomass estimate x (the rate/biomass):

$$\text{excreted N} = \text{EXCN}_z (Z)(\text{XLIM}_z) + \text{EXCN}_a (A)(\text{XLIM}_a)$$

$$\text{NH}_3 = \text{NH}_3 + \text{excreted N} - \text{uptake}$$

where

Z, A = biomasses of zooplankton and anchovy

$\text{EXCN}_{z,a}$ = the excretion rates of zooplankton and anchovy per unit biomass

XLIM_z = the density-dependent food limitation terms (Ivlev)

Notice that this formulation assumes nutrient excretion only when grazing is taking place and in direct proportion to the rate of grazing. In my opinion, this is probably not a strong assumption since excretion certainly continues in a starving animal due to respiration, etc. The only basis for this assumption is the patchiness argument mentioned earlier concerning the possible feeding threshold. If the Ivlev equation is interpreted to mean that herbivores are only found in water where food is abundant, then the reduction of grazing is appropriate. This, however, is not the conventional interpretation. It is interesting to note that without this assumption, the excretion of nutrients is much too large, and the model gives less satisfactory results. The assumption is therefore included here, partly because Walsh used it, but more careful evaluation of the excretion formulation seems necessary before results may be interpreted in detail. Clearly, the uncertainty in these formulations is compounded by the uncertainty in the empirical data used in the rate estimates. Adequate formulations depend ultimately on increasing our data base in the area of herbivore excretion, as in others.

Detritus. Because the role of the anchovy is only crudely represented here, detritus is not considered. Detritus in the form of zooplankton and anchovy fecal pellets (unassimilated ingested phytoplankton) is probably an additional food source for the herbivores, and may significantly contribute to the particulate nutrient levels in the water. For our purposes initially, no herbivore dynamic mechanisms are included in the model, and the role of detritus is ignored.

Computation Procedure

Stability. The grid scheme used in the circulation model UPWELL was selected to be the same as that of Walsh: 10 kilometers x 10 kilometers x 10 meters. For the velocity field used for both the autumn and winter system, numerical stability is not a problem for the same criteria mentioned by Walsh (Wp 217).

Steady State. The model is run to approximate a steady-state condition. Walsh mentions that for his model this is achieved in 1800 simulated hours (c 80 days), and my model also reached a stable condition in about 50 days. The criterion for steady state was a total change in phytoplankton in all grids in the top two layers less than 0.1 percent.

Even though the model is used to represent only steady-state, it seems possible that time-variable simulations could be attempted too. In fact, the diel variation of Walsh seems to suggest that perhaps the interacting rates may track appropriate time-variations in a realistic way. This may prove a useful tool in investigating the spatial heterogeneity that may result from variations in the velocity fields along shore and offshore.

Integration Method. The solution of the differential equations of the model is accomplished using a method I developed for the Narragansett Bay (Rhode Island) model. The rates express basic growth processes, and thus suggest the use of exponential equations. Thus, instantaneous rates for growth and grazing may be evaluated simultaneously in the following form:

Let

GP = growth rate of Phyto (day^{-1}), i.e., $\text{mg C}/(\text{mg C} \cdot \text{day})$

gz = grazing rate of herbivores (day^{-1}), i.e., $\text{L}/(\text{L} \cdot \text{day})$

P_0 = initial condition of phytoplankton (mg C/L)

Then

$$P = P_0 e^{(GP-gz)t}.$$

This equation represents the exact integral of the differential equation for any time interval (t) during which the two rates (GP, gz) are constant. The differential equation is:

$$dp = (GP - gz)(P) dt$$

Conventionally, the differential equation is solved using a scheme of numerical integration--for each small time change, the value of dp is calculated and added to the present value of P for the next iteration. This is the method used by Walsh.

Thus

$$dp_1 = (GP - gz)P_0 dt \quad (1)$$

$$P_1 = P_0 + dp_1$$

$$dp_2 = (GP - gz)P_1 dt \quad (2)$$

$$P_2 = P_1 + dp_2$$

etc.

When the exact integral of simultaneous rates is used, the rates must all be of the same units. That is, both GP, the growth rate of the phytoplankton and the grazing rate of the herbivores, have only the units time^{-1} . The grazing of herbivores is originally calculated as a ration ingested (e.g., mg C/hour). It is necessary to change this ration into a filtering rate of the correct units.

$$\text{Ration} = I_z(Z)(\text{XLIM}_z) + I_a(A)(\text{XLIM}_a) \quad (\text{mg C/L}\cdot\text{hr})$$

$$gz = [\text{Ration (mg C/L}\cdot\text{hr)}] / [P \text{ (mg C/L)}]$$

The filtering rate gz (hour^{-1}) represents the rate at which the combined grazing of the zooplankton and anchovy occurs. If the available food (P) is small, the herbivores will feed very fast, trying to get the desired ration. In some cases, gz may exceed 1.0--every liter of the water column is filtered more than one time. But because the rate is integrated in the exponential form, some phytoplankton will always remain. For example:

$$gz = 1.0 \text{ day}^{-1}$$

$$P_1 = P_0 e^{(-gz \cdot \text{day}^{-1})}$$

then

$$P_1 = 0.368 P_0$$

Thus, 36.8 percent of the original phytoplankton will remain after one day of intensive grazing, compared to 0.0 remaining if the conventional finite-difference integration method is used.

To correctly evaluate the uptake of nutrients and the actual amount of phytoplankton consumed by the herbivores, the exponential equation must be used again. The net result of one rate working in combination with other rates simultaneously may be specified.

If:

GP = growth rate

gz = filtering rate

Then:

$$PNET = -GP \times [P_0 (1 - e^{(GP-gz)})]/(GP - gz)$$

$$RTN = gz \times [P_0 (1 - e^{(GP-gz)})]/(GP-gz)$$

Example. GP = +0.698 day⁻¹ and gz = 0.500 day⁻¹, growth is a little more than grazing.

After one day:

$$P = P_0 e^{(0.693-0.500)} = 1.213 P_0$$

$$PNET = -0.693 \times P_0 (1 - e^{0.193})/(0.193) = 0.765 P_0$$

$$RTN = 0.500 \times P_0 (1 - e^{0.193})/(0.193) = -0.552 P_0$$

$$\text{Final change} = PNET + RTN = 0.765 P_0 - 0.552 P_0 = 0.213 P_0$$

$$P = P_0 + 0.213 P_0 = 1.213 P_0$$

In this example, the exact integral shows that the final change in the phytoplankton is 1.213 P₀, and the other equations show that this change results from growth of 0.765 and grazing of 0.552. The uptake of nutrients must be computed from the PNET, since this is the total growth represented in the compartment, even though some is lost to grazing. Similarly, when calculations including the growth of the herbivores are added to the model, the actual ration consumed by them is the value RTN.

The method used in this model, in contrast to the finite difference schemes most frequently employed, evaluates the exact integral over "dt" so that the only mathematical approximation is the assumption that the rates are constant over the time interval. For the simulations completed up to now, grazing (gz) is assumed to be constant at all times (a 24-hour average seasonally). The factors which determine

GP are recalculated at short intervals. Nutrient limitation is usually the most rapidly changing condition, so that factor NUTLIM is computed every iteration in the simulation (hourly). Light limitation (LTLIM) only varies with changes in the extinction coefficient due to changes in phytoplankton biomass. These changes are relatively slow, and thus are computed only one time each day. The maximum growth rate as a function of temperature (G_{max}) depends only on the temperature field which is constant throughout the simulation. Thus this computation is done for every grid in the system only during the first iteration of the simulation.

During each iteration, the program computes the nutrient limitation terms (NLIM, PLIM, SILIM) from which the most limiting nutrient term is chosen (MXLIM). GP is computed using the G_{max} and the daily value of LTLIM. The uptake of the nutrients is computed using the predicted growth of phytoplankton (PNET). The total changes of each of the nutrients and the phytoplankton for each of the grids are used in the UPWELL circulation program in combination with the diffusion and advection changes to compute the final change in each grid every hour.

RECOMMENDATIONS FOR CONTINUED RESEARCH

Model-Related Recommendations

To speed up the preliminary development of the ecological model, the three-dimensional circulation program (UPWELL) was modified to include only two dimensions. This form is well suited for many analyses because it is executed in a fraction of the time on the computer and is easier to deal with for the programmer. However, the questions of longshore gradients in horizontal and vertical velocities, which may be related to patchiness, cannot be evaluated in this simplified version. It would be desirable if a duplicate deck were prepared, on which the modifications were made to allow three-dimensional ecological simulations. The transition has been anticipated and only a few changes in dimension statements should be necessary.

Another question related to the circulation problem is the relative role of the advection and diffusion components of the mixing equation. In other words, what are the values of the eddy coefficients, especially in surface layers and regions of strong shear associated with upwelling? The model UPWELL may be used alone to evaluate the effect of different values. For example, given only boundary values for nutrients, different eddy coefficients will result in different depth gradients which can be used to suggest the best choice of this parameter.

Perhaps the most valuable improvement in the model which may be easily undertaken at this time is to include diurnal variations in some factors. For example, diel patterns of light may be represented by a simple sine equation, and the photosynthetic response of phytoplankton may then be evaluated, using the Steele equation, at each time and depth. The present assumptions calculate only a 24-hour average of the Steele equation integrated over each depth interval for the total day using the complicated equation of DiToro. Additional modifications appropriate here are vertical migration and grazing of herbivores.

Other Recommendations

The following are valuable experiments and field observations suggested by early work with the model.

The self-shading, extinction coefficient relationship, especially the appropriate value of k_0 , should be verified. A simple regression analysis of observed extinction coefficient (k) with Chl a (or plant carbon) will indicate both the intercept k_0 and an appropriate relationship.

The C:Chl ratio is used in the model to relate the state variable, carbon, to the more frequently measured biomass estimate, chlorophyll. Direct comparison of model results to field data requires as good an estimate as possible of this ratio and its range.

Similarly, the appropriate ranges of carbon:nutrient ratios for the phytoplankton species are important values which need better estimation.

Nutrient kinetic experiments suggested by the model formulation of the most limiting nutrient would be very valuable. Additional surveys of appropriate half-saturation constants for growth (K_s) and enrichment experiments to evaluate nutrient limitation in the natural system would be important.

Grazing rates, excretion rates, feeding thresholds and biomass estimates of zooplankton as well as anchovy are essential before their role in the upwelling ecosystem may be even adequately approximated in the model. The formulation in the present model is certainly crude and serves primarily to point out areas where additional research would be extremely useful.

The potential role of switch-feeding of the anchovy between phytoplankton and zooplankton is another valuable line of research to pursue. The question of what factors may control this switching for juvenile and adult anchovy lends itself nicely to a combined experimental and modeling research effort.

The potential role of detritus as a food source to zooplankton and anchovy also deserves future study. In many other marine and estuarine systems, detritus may be an important food or food supplement, and analysis of this possibility in the upwelling systems would be interesting.

THE ECOLOGICAL COMPUTER PROGRAM

The following is a short guide for the use of the physical circulation model UPWELL and the ecological subroutines, ECOS and PHYTO. While a detailed, line-by-line description of the programs is not possible, this discussion of the critical variables and main input parameters is necessary for continued use of the model. The overall program-flow may be outlined as:

UPWELL

Initial specification, assignment of certain parameters;
 *READ velocities in y and z dimension for 1 plane (x=1);
 *READ temperature field; WRITE temp for reference;
 Convert input velocities (cm/sec) to program units (m/hr);
 Assign program control variables, and accumulators, etc.;
 Average pairs of input velocities to get center-cube flows;
 If CHECK = 1, confirm continuity and grid-time stability;
 WRITE new velocity field - flows at center of grid cubes;
 *READ initial conditions for ecological variables, using
 Fortran NAMELIST input option.

Begin iterations for each time-step:

Update timer and output-control variables;
 Call ECOS: determine non-physical rates of change each hour;
 Calculate boundary values using no-diffusion condition;
 (At Air and Land, $C_b = C$ so no concentration gradient exists at boundary b; at Deep and Offshore boundaries, constant initials kept);
 Calculate advection and diffusion parts of change equation;
 Integrate the physical and biological changes:
 $DCDT = \text{Biol changes (R)} - \text{advection (DCZ, DCY)} + \text{diffusion (D2CZ, D2CY)}$;
 Transfer new concentrations into array VAL for ECOS and PHYTO accounting for uptake of NH_4 first, then NO_2NO_3 as required by assumption of inhibition of uptake by phytoplankton;
 If IOUT=1 for output, WRITE arrays of state variables;
 Subroutine STDYST checks for steady state of change if called.

End iterations for each time-step

Call PROFIL subroutine to output final results

(Note additional output statements at end of program if desired to WRITE partial change values DCZ, D2CZ, etc.)

*See sample data input example, figure 2.

SUBROUTINE ECOS (The derivation of the formulations are given in the official report; a brief outline of the program follows.)

Data assignments for grazing and excretion of herbivores, presently as DATA statements, may be changed to a READ;
 Call PHYTO;
 Calculate excretion and grazing pressure by the zooplankton and anchovy (presently this is done only in the first iteration because constant rates are assumed--when a better formulation is used, this should be done every time);
 Compute food-limitation term for herbivores;
 Compute excretion and grazing corrected for food limitation (this is done every iteration because phyto. is changing);
 Compute final rates of change (per hour) for all state variables;
 Return to UPWELL for integrations of rates.

SUBROUTINE PHYTO

Data assignments for important coefficients;
 Determine maximum potential growth rate for each grid based on the temperature, GMAX (this is only done once since temperature is constant);
 Determine degree of light limitation LTLIM (this is done once every day, since it depends on light which is assumed constant and the extinction coefficient which changes slowly due to self-shading by phytoplankton);
 Calculate kinetic nutrient limitation MXLIM based on the most limiting nutrient NLIM, PLIM, SILIM;
 Assign correct symbol to array LSIGN to indicate the limiting nutrient for output.
 Calculate the estimate of net primary productivity GP as the product of GMAX x LTLIM x MXLIM; GP is the average rate of productivity ($=C^{14}$) during the 24-hour day, but it is an hourly rate, to agree with the time-step of UPWELL;
 Output useful variables for all grids at each output interval (IOUT = 1);
 Return to ECOS to complete rate-of-change calculations for the other state variables.

General Programming Considerations for UPWELL

Program used with ecological model was modified to only compute Y-Z plane, no X-direction (along shore) change is possible. This was done to save computer time and money. The basic model UPWELL is, however, three-dimensional, and conversion back to this form should be straightforward:

a. Dimensions should be increased in UPWELL to allow a 10 x 10 x 10 array to replace the present 1 x 10 x 10. Concentration and change arrays include extra boundary grids and also must be changed to 5 x 12 x 12 x 12 from present 5 x 1 x 12 x 12.

b. The X-direction changes must be replaced in the program, both in the DIMENSION statements (VX, DCX, D2CX) and in the body of the program where these are calculated. The original three-dimensional version of UPWELL may be used for comparison, but note that the boundary conditions are different. The no-diffusion boundary condition of the recent version is correct for the center-grid velocities.

The computational field of grids in the physical model is 1 x 10 x 10 (or 10 x 10 x 10 for three-dimensional) so velocities and rates arrays are dimensioned accordingly. Advection and diffusion calculations require an additional grid point at each boundary, so the array C is in dimensions of 3 x 12 x 12. It is important in the program calculations to carefully keep track of which element of the C array agrees with elements of DCY, D2CZ, R, etc. For example, C(2,2,2) = R(1,1,1) for each substance that is mixed by the model.

The array VAL is used to transfer the concentrations of the state variables (PPL, NH₄, etc.) between the subroutines and the main program UPWELL through the common block /VALUES/. VAL(500) is a one-dimension array because the many calculations in the subroutines ECOS and PHYTO may be completed independent of the physical location of the grid. (This is more efficient that the four-dimensional array C used in UPWELL because of the way the machine evaluates multi-dimensional subscripts every time they occur.) The concentrations of the state variables C are passed into array VAL for use in the subroutines, and any increase in the size of the grid field must have an increase in the dimension of VAL also.

Definitions of key variables in UPWELL include:

VX, VY, VZ = velocities in the along shore, offshore, and down directions. Input as cm/sec across grid boundaries; converted in the program to center-grid averages as cubic meters per hour.

D2CX, D2CY, D2CZ = partial change due to diffusion.

DCX, DCY, DCZ = partial change due to advection.

EDX, EDY, EDZ = eddy diffusion coefficients, assumed constant in x and y direction, variable with depth. Thus, EDZ(1) is coefficient for diffusion between Z₁ and Z₂. A great deal of uncertainty about the correct values for EDZ with depth of zones of upwelling exists, and different values of this parameter should be tested in the model.

TEMP = temperature field assigned to grids. Constant with time.

NX, NY, NZ = number of grids in each dimension.

MXGRID = maximum number of grids = NX x NY x NZ. This number is used in sequential iterations of the concentrations stored in one-dimensional array VAL in ECOS and PHYTO.

NC = number of state variables (concentrations) for UPWELL.

BX, BY, BZ = array of size-limits including extra non-computational boundary grids. BX = NX + 2, etc.

C = array containing the concentrations of the state variables in UPWELL, dimensioned C(NC, BX, BY, BZ).

DX, DY, DZ = length in meters of the grids in the three-dimensions (presently 10km x 10km x 10m or 10000 x 10000 x 10m).

DT = time-step of iterations, in hours (presently DT = 1 hr.).

LAST = duration of the total simulation run, in hours. Steady-state seems to take 30-60 days, LAST=720 - 1440 hrs.

CHECK = confirm continuity (conservation of water) and numerical stability of grid-size and time-step if CHECK = 1. This should be done once when new velocity fields are tried. Thereafter CHECK = 0 will avoid the checks. Note that the continuity check may indicate "water not conserved" for very insignificant volumes due to machine rounding error. This may be ignored after determining that the error is small.

General Programming Considerations for ECOS

The flow of this subroutine is not complicated. Calculations for all grids are done in the one-dimensional array of state variables P(MXGRID), NH4(MXGRID), etc. Rates of change DP, DNH4, etc., are calculated and returned to UPWELL by the common block /CHANGES/.

Note that all calculations for herbivore grazing and excretion are not done in every iteration, since average rates are not variable in time in the present model. This is one of the first changes that will be useful to make in the model.

Final rate-of-change estimates are based on the exponential evaluation of instantaneous growth and grazing. A discussion of this method is in the final report.

Definitions of key variables in ECOS:

ANCH = biomass estimates of anchovy, no. of fish/L. Presently two values are specified, one for winter and one for autumn.

ZOOP = biomass estimates of zooplankton, mg dry wt./L. two seasons.

AEXCN, ZEXCN = rates of nitrogen excretion, ug-at N/L unit biomass. Two rates are specified for fish for different seasonal size.

ARTN, ZRTN = rates of nitrogen excretion, ug-at N/L unit-biomass.
Two rates are specified for fish for different seasonal size.

GRAZK = food-limitation coefficient for the Ivlev equation, L/mg C.

ZPO, APO = feeding threshold for no feeding of zooplankton and fish.

SEASON = control of which season is selected for the herbivore biomass, etc. 1 = autumn, 2 = winter, 0 = no herbivores.

***Variables above presently must be specified for the simulation internally by Fortran DATA statements; in the future it might be desirable to read these values.

XLIMA, XLIMZ = food-limitation fraction to adjust grazing pressure and excretion values (unitless fraction).

RATION = total preferred ingested ration by herbivores; the final realized ration must be calculated from the instantaneous grazing rate FILT in the growth equations (mg C/hr).

FILT = the predicted filtration rate of herbivores necessary to achieve the preferred ration based on available food.

CHG = net phytoplankton rate of change = growth (GP) minus grazing (FILT).

DP(grid) = predicted change in phytoplankton (mg C/hr) based on the exponential evaluation of the growth and filtration rates.

PNET = net primary production of the phytoplankton evaluated considering the fact that grazing was occurring simultaneously with growth.

DN¹⁴(grid) = hourly change in ammonia, due to uptake by the phytoplankton (PNET) and excretion by the herbivores.

DPO4(grid) and DSi(grid) = hourly change in phosphate and silicate.

General Programming Considerations for PHYTO

All calculations concerning the growth rate of phytoplankton are not done every iteration to save computer execution time. Since the temperature is constant for all computational grids, temperature-dependent maximum rates are only computed one time. Light limitation is calculated once every 24 hours, but nutrient limitation is determined every hourly time-step.

Although the final growth rate estimate (GP) represents an hourly instantaneous rate, it is based on the assumption of no diel variation; i.e., no day and night variations are represented during one day's 24-hour iterations. All conditions of nutrient availability change every hour, but the assumed light equation (LTLIM) corrects for the day-night effect.

In this subroutine as well as ECOS, the one-dimensional arrays are used for the state variables. It is necessary to compute the level of light reaching each depth, however, so the actual location of each grid in the water column had to be determined. In the calculation of LTLIM, vertical columns of grids are computed in sequence from surface to bottom, with the light level continuously decreasing with depth through the series.

Definitions of Key Variables in PHYTO

C\$NP, C\$PP, C\$SIP = carbon-to-nutrient ratios for the phytoplankton. Values for these important conversion factors are input to the program as ratios by atoms, C:N, C:P, C:Si. Because the units in the model are in milligrams of carbon, it is necessary to convert the ratios to $\mu\text{g-at/mg C}$ in PHYTO.

IOPT = the optimum light for photosynthesis. The actual value of this is not too important; only the ratio of the incident light to the optimum is used in the equations.

RADN = radiation incident at the surface of the ocean. The units may be irradiance or insolation, but it is important that the choice of IOPT be based on the same units.

F = photo-period, or day length, expressed as a fraction of a day.

KO = extinction coefficient of water with no phytoplankton.

KSN, KSP, KSSI = half-saturation constants for growth of phytoplankton for the three nutrients (Michaelis-Menton or Monod).

DTT = conversion for the hourly rate of growth from the 24-hour value.

GMAX(grid) = maximum growth rate of phytoplankton as a function of temperature (based on the work of Eppley, 1972).

EXCOEF(grid) = estimated extinction coefficient due to absorption of light by the phytoplankton (converted from the equation of Riley, 1956).

LTLIM(grid) = limitation to growth due to less than optimum light integrated over 24 hours for the depth interval of each grid.

NTOT = total nitrogen available for phytoplankton growth,
 $\text{NH}_4 + \text{NO}_2 + \text{NO}_3$.

NLIM, PLIM, SILIM = kinetic factors for the limitation of growth due to nutrient concentrations (based on the hyperbolic Monod or Michaelis-Menton equation).

MXLIM = the minimum of NLIM, PLIM, SILIM: the "most limiting" nutrient. (Notice that an alternative way to select the limiting nutrient is in the program as comments.)

GP(grid) = estimated growth rate of the phytoplankton. The value is an instantaneous rate (hour^{-1}) representing net primary production, approximately the same as C^{14} data.

OUTEX, OUTLT, OUTMX, OUTGP, LSOUT = arrays used for output of the part of the state variable arrays that are used in the calculations. (Now only 70 of the 100 grids are printed.)

Programming Considerations--Supplementary Subroutines

BLOCK DATA. This subroutine is necessary to assign initial values to variables and parameters placed in COMMON. It also would be possible to read these as inputs with Fortran READ statements.

SUBROUTINE PROFIL. This program is only to produce output of the simulated results in an easily readable format. Profiles of grid values for rates and concentrations offshore and with depth are produced for the following variables:

CHL = estimated chlorophyll distribution assuming C:Chl = 35.

PN = net phytoplankton primary productivity [$\text{mg C} / (\text{m}^3 \cdot \text{day})$]. This must be calculated from the growth rate and the biomass values.

AR = assimilation ratio, $\mu\text{g C} / (\mu\text{g Chl} \cdot \text{day})$.

DP = community production, i.e., net change of phytoplankton due to growth and grazing. This is the instantaneous hourly rate times a conversion factor to give a rate with units $\text{mg C mg C}^{-1} \text{ day}^{-1}$.

Profiles of the nutrient concentrations also may be easily obtained by adding additional WRITE statements.

SUBROUTINE STDYST. This program determines if the changes in the phytoplankton compartment are small enough to represent steady-state conditions. The criterion used is total change in the phytoplankton biomass in the top 20 grids (0-20m and 0-100km offshore) of less than 0.1 percent between successive calls of the subroutine STDYST. In the simulations up to now, STDYST is only called when output of the program variables occurs every five simulated days. Even with this rigorous test, the program converges to steady-state in 25 to 60 simulated days, depending on the exact conditions of the run.

T C

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C PROGRAM UPWELL AND ECOS AND PHYTO FOR PEKU PROJECT APRIL 1975
C DECK MODIFIED FOR ONLY 1 Y-Z PLANE, NX = 1
C ALL VX, DCX, D2CX OMITTED
C DIMENSION
1 EDZ(10),
2 C( 5, 3, 12, 12), R(1, 10, 10, 5), TEMP( 1, 10, 10),
3 DCY( 5, 1, 10, 10),
4 DCZ( 5, 1, 10, 10),
5 D2CY( 5, 1, 10, 10), D2CZ( 5, 1, 10, 10)
INTEGER BX, BY, BZ, DAY, BX1, BY1, BZ1
1, ID(15)/'PPL', 'NH4', 'NOX', 'PO4', 'SI',
2 'VX', 'VY', 'VZ', 'DCX', 'DCY', 'DCZ', 'D2CX', 'D2CY', 'D2CZ', 'T' /
COMMON /CNTRL/MXGRID, IOUT, NX, NY, NZ, DX, DY, DZ, DT, DAY, HOUR, TEMP
3 /VALUES/VAL(500) /CHANGE/ R
NAMELIST /INITL/ VAL
DATA C/2160*0./
C DIMENSIONS ARE ( C, X, Y, Z) -- INDICES ( N, I, J, K)
C =====> INITIALIZE EDDY DIFFUSION PARAMETERS
C HORIZONTAL PLANE EDX & EDY = 1.0E6 CM2/SEC
C VERTICAL PLANE EDZ = 5.0 CM2/SEC ABOVE 20 M, 1.0E-3 BELOW
C COEFFICIENTS MAY HAVE TO BE DIMENSIONED IN A NON UNIFORM FIELD...
EDX=1.0E6 * 0.36
EDY=EDX
DATA EDZ/10* 0.36E-3/
EDZ(1)=1.8
EDZ(2)=1.8
C =====> INITIALIZE VELOCITY PARAMETERS
C READ IN VY AND VZ -- VX INITIALLY ALL 0.
READ(5,10)((VY(1,J,K),J=1,10),K=1,10),
1 ((VZ(1,J,K),J=1,10),K=1,10)
10 FORMAT(10F7.3)
C READ IN TEMPERATURE FIELD
READ(5,10)((TEMP(1,J,K),J=1,10),K=1,10)
I=1
WRITE(6,910)ID(15),I,((TEMP(I,J,K),J=1,NY),K=1,NZ)
C CONVERT FROM CM/SEC INPUT TO PROGRAM UNITS M/HR; AND FILL ARRAYS
C (36 M/HR PER CM/SEC )
DO 20 J=1,NY
DO 20 K=1,NZ
VY(1,J,K)=VY(1,J,K)*36.0
1 * 2.0
VZ(1,J,K)=VZ(1,J,K)*36.0
1 * 2.0
20 CONTINUE
C =====> PREPARE FOR COMPUTATION ITERATIONS
NC=5

```

NO VX

NO DCX

NO D2CX

M2/HR

M2/HR

M/HR

RAPIDO

M/HR

RAPIDO

```

LAST=24
LAST=LAST*51
CHECK=1.
CHECK=0.
IPG=0
DX2=DX*DX
DY2=DY*DY
DZ2=DZ*DZ
T=0.
DAY=1
C RESET COUNTERS FOR SPECIFIC BOUNDARY LIMITS FOR THIS PROBLEM
NX=1
NY=10
NZ=7
PX=NX+2
PY=NY+2
PZ=NZ+2
RX1=PX-1
RY1=PY-1
RZ1=PZ-1
C
AXY=DX*DY
AXZ=DX*DZ
AYZ=DY*DZ
VXMAX=0.
VYMAX=0.
VZMAX=0.
I=1
C (NOTE: IF MAX ARRAY SIZE IS INCREASED, CHANGE '10' IN IF STMTS BELOW)
DO 30 J=1,NY
J1=J+1
IF(J1.GT.10)J1=10
DO 30 K=1,NZ
K1=K+1
IF(K1.GT.10)K1=10
C AVERAGE VELOCITIES AT GRID BOUNDARIES TO GET CENTER POINT VALUES
VY(I,J,K)=(VY(I,J,K)+VY(I,J1,K))/2.0
VZ(I,J,K)=(VZ(I,J,K)+VZ(I,J,K1))/2.0
IF(CHECK.NE.1.)GO TO 29
C CONFIRM CONTINUITY (CONSERVATION OF WATER) FOR ALL GRIDS
DATA DMASX/0.,,DRSVX/0.,,VXMAX/0.
DMASSY=(VY(I,J,K)-VY(I,J1,K))*AXZ
DMASSZ=(VZ(I,J,K)-VZ(I,J,K1))*AXY
DMASS=DMASX+DMASSY+DMASSZ
IF(DMASS.NE.0.)WRITE(6,24)I,J,K,DMASX,DMASSY,DMASSZ,DMASS
26 FORMAT(' WATER NOT CONSERVED IN GRID (' ,3I3,') DMASS X,Y,Z=',
1 3E15.4,1E20.8)
C CHECK STABILITY CRITERIA

```

HOURS

```

      ABSVY=ABS(VY(I,J,K))
      ABSVZ=ABS(VZ(I,J,K))
      IF(ABSVY.GT.VYMAX)VYMAX=ABSVY
      IF(ABSVZ.GT.VZMAX)VZMAX=ABSVZ
29  CONTINUE
30  CONTINUE
      I=1
      WRITE(6,910)ID(7),I,(( VY(I,J,K),J=1,NY),K=1,NZ)
      WRITE(6,910)ID(8),I,(( VZ(I,J,K),J=1,NY),K=1,NZ)
      IF(CHECK.NE.1)GO TO 32
C   ADVECTION CRITERIA:
      DATA XSTAR,STABX/2*0./
      YSTAR=VYMAX*DT/DY
      ZSTAR=VZMAX*DT/DZ
C   TURBULENT DIFFUSION CRITERIA:
      STABY=EDY *DT/DY2
      STABZ=EDZ(1)*DT/DZ2
      WRITE(6,95)XSTAR,YSTAR,ZSTAR,STABX,STABY,STABZ
32  CONTINUE
35  FORMAT('ADVECTION STABILITY CRITERIA X,Y,Z:',3E12.4,
1  ' (MAXIMUM FOR EACH DIMENSION)'/
1  ' TURBULENT STABILITY CRITERIA X,Y,Z:',3E12.4)
      DATA INSET,IDSET/5,0/
      IF(INSET.EQ.5) READ(5,INITL)
      IF(INSET.NE.5) READ(INSET,915)DAY,VAL
      WRITE(6,917)INSET,DAY
C   INPUT INITIAL CONDITIONS FOR PPL, NH4, NO2NO3, PO4, & SI
C
C   =====> BEGIN ITERATIONS
      DO 1000 IT=1,LAST
      T=T+DT
      HOUR=AMOD(T,24.)
      IF(HOUR.EQ.0.)DAY=DAY+1
C   INPUT DETERMINES FREQUENCY OF OUTPUT
      INPUT=AMOD(T, 240.)
C   CALL SUBROUTINES HERE TO DETERMINE NON-PHYSICAL RATES OF CHANGE IN C
      CALL ECOS
C   TRANSFER VALUES INTO C-ARRAY FOR MIXING
      I=2
      IGRID=0
      DO 40 K=2,87
      DO 40 J=2,8Y1
      IGRID=IGRID+1
      C(1,I,J,K)=VAL(IGRID )
      C(2,I,J,K)=VAL(IGRID+100)
      C(3,I,J,K)=VAL(IGRID+200)
      C(4,I,J,K)=VAL(IGRID+300)
      C(5,I,J,K)=VAL(IGRID+400)

```

```

40  CONTINUE
C
C  DETERMINE BOUNDARY VALUES FOR CONCENTRATIONS
C  I.E. AT COAST AND SURFACE, NO DIFFUSION: C(8) = C(8-1)
C  LATERALLY AND OFFSHORE, C(8) = C(8-1) (OR UNCHANGING)
      I=2
      DO 100 J=1,8Y
      DO 100 K=1,8Z
      DO 100 N=1,NC
        IF(J.EQ. 1)C(N,I,J,K)= C(N,I,2,K)
        IF(J.EQ.8Y)C(N,I,J,K)=C(N,I,8Y1,K)
        IF(K.EQ. 1)C(N,I,J,K)= C(N,I,J,2)
        IF(K.EQ. 8Z)C(N,I,J,K)= C(N,I,J,8Z1)
        NO CHANGE IN DEEP BOUNDARY
100  CONTINUE
C  SPECIAL CALCULATIONS NEEDED FOR NON-COMPUTATIONAL GRIDS WITHIN BOUNDARIES.
      I=2
      DO 110 N=1,NC
        (I,2,8) IS A PHYSICAL BOUNDARY.
        C(N,I,2,8)=C(N,I,2,9)
110  CONTINUE
C
C  CALCULATE PARTIAL CHANGES IN X, Y, & Z DIRECTIONS DUE TO ADVECTION AND
C  TURBULENT (EDDY) DIFFUSION
      I=1
C  MAKE X C INDICES ARE ONE LARGER THAN LOOP INDEX; I => C(I-1)
      I1=I+1
      I2=I+2
      DO 150 J=1,8Y
      J1=J+1
      J2=J+2
      DO 150 K=1,8Z
      K1=K+1
      K2=K+2
      AY=1.
      IF(VY(I,J,K).GT.0.)AY=0.
      AY1=1.-AY
      AY2=AY1-AY
      AZ=1.
      IF(VZ(I,J,K).GT.0.)AZ=0.
      AZ1=1.-AZ
      AZ2=AZ1-AZ
      DO 150 N=1,NC
        DCY(N,I,J,K)= VY(I,J,K)*(AY*C(N,I1,J2,K1)+AY2*C(N,I1,J1,K1)
          - AY1*C(N,I1,J,K1))/DY
        DCZ(N,I,J,K)= VZ(I,J,K)*(AZ*C(N,I1,J1,K2)+AZ2*C(N,I1,J1,K1)
          - AZ1*C(N,I1,J1,K))/DZ
        TWOC=C(N,I1,J1,K1)+C(N,I1,J1,K1)
        DZCY(N,I,J,K)=(DY
          *(C(N,I1,J2,K1)+C(N,I2,J,K1)-TWOC)/DY2
          =C(I1)
          =C(I1+1)

```

```

150 D2CZ(N,I,J,K)=EDZ(      K)*(C(N,I1,J1,K2)+C(N,I1,J1, K)-TWOC)/DZ2
C CONTINUE
C SUM PARTIAL CHANGES AND INTEGRATE
I=1
I1=I+1
DO 200 J=1,NY
J1=J+1
DO 200 K=1,NZ
K1=K+1
DO 200 N=1,NC
DCDT=R(I,J,K,N) - DCY(N,I,J,K) - DCZ(N,I,J,K) NO DCX
1 C(N,I1,J1,K1)=C(N,I1,J1,K1) + DT*DCDT NO D2CX
200 CONTINUE
C TRANSFER NEWLY MIXED CONCENTRATIONS BACK INTO ARRAY VAL
IGRID=0
I=2
DO 160 K=2,11
DO 160 J=2,8Y1
IGRID=IGRID+1
VAL(IGRID)=C(I,I,J,K)
IF(VAL(IGRID).LT.0.)VAL(IGRID)=0.
VAL(IGRID+300)=C(4,I,J,K)
VAL(IGRID+400)=C(5,I,J,K)
C USE NH4 UNTIL DEPLETED, THEN USE NO2NO3:
DEBT=C(2,I,J,K)
IF(DEBT.GE.0.)GO TO 158
DEBT=DEBT+C(3,I,J,K)
IF(DEBT.LT.0.)DEBT=0.
VAL(IGRID+100)=0.
VAL(IGRID+200)=DEBT
C(2,I,J,K)=0.
C(3,I,J,K)=DEBT
GO TO 160
158 VAL(IGRID+100)=DEBT
VAL(IGRID+200)=C(3,I,J,K)
160 CONTINUE
C IF(IOUT.NE.1)GO TO 1000
C WRITE Y-Z PLANE
I=2
DO 300 N=1,NC
IPG=IPG+1
IF(MOD(IPG,5).EQ.1)WRITE(6,900)
WRITE(6,913)DAY,HOUR,ID(N),I,(C(N,I,J,K),J=2,8Y1),K=2,8Z1)
300 CONTINUE
C CHECK TO SEE IF STEADY STATE HAS BEEN ACHIEVED

```



```

      CALL STUYST
1000  CONTINUE
      IF(IQSET.NE.0)WRITE(IQSET,915)DAY,VAL
      IF(IQSET.NE.0)WRITE(6,916)IQSET
      CALL PRGFIL
      STOP
C      WRITE(6,910)ID(4),((DCX(1,1,J,K),J=1,NY),K=1,NZ)
C      WRITE(6,910)ID(5),I,((DCY(1,1,J,K),J=1,NY),K=1,NZ)
C      WRITE(6,910)ID(6),I,((DCZ(1,1,J,K),J=1,NY),K=1,NZ)
C      WRITE(6,910)ID(7),((D2CX(1,1,J,K),J=1,NY),K=1,NZ)
C      WRITE(6,910)ID(8),((D2CY(1,1,J,K),J=1,NY),K=1,NZ)
C      WRITE(6,910)ID(9),((D2CZ(1,1,J,K),J=1,NY),K=1,NZ)
900    FORMAT(1H1)
910    FORMAT('D',5X,A4,' X-GRID',14//(' ',10X,10F10.3))
C      WRITE(6,912)DAY,HOUR,ID(N),I,((C(N,I,J,K),J=1,NY),K=1,NZ)
912    FORMAT('D',15,' HOUR',F6.2,' CONCENTRATION ',A4,' X GRID',14
1/(' ',12F10.3))
913    FORMAT('D',15,' HOUR',F6.2,' CONCENTRATION ',A4,' X GRID',14
1/(' ',10F10.3))
915    FORMAT(15/(10F8.5))
916    FORMAT('D ==> OUTPUT INITIAL CONDITIONS TO SET',15/)
917    FORMAT('D INPUT DATA READ FROM SET',15,', EFFECTIVE START-UP ON DA
LY',15)
      END

```

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```

BLOCK DATA
COMMON /CNTRL/MXGRID,ICLT,MX,NY,NZ,DX,DY,DZ,DT,DAY,HOUR,T(100 )
1 /PHYT/GMAX(100 ),LTLIM(100 ),MXLIM(100 ),LSIGN(100 ),GP(100 )
2 /CNVRT/ C$NP,C$PP,C$SIP
1 /CHANGE/R(500)
INTEGER DAY
REAL GMAX,LTLIM,MXLIM,GP
DATA GMAX,LTLIM,MXLIM,GP / 400*0.0/
C      (106, 16, 10, 1) C:N:SI:P 6Y ATCMS
DATA C$NP,C$SIP,C$PP/ 16., 10., 1./
DATA      MXGRID,NX,NY,NZ,DX,DY,DZ,DT,DAY,HOUR
1 /      / 100, 3,10,10,2*1.E4,10.,1.,0,0. /
DATA R/500 *0./      .LSIGN/ 100*' '/
END
ATUMS

```

```

SUBROUTINE FCOS
C
C   HERBIVORE GRAZING AND EXCRETION INCLUDED HERE:
C   BIOMASS ESTIMATES FOR HERBIVORES: FISH/L, MG DW ZOO/L
C   REAL ANCH(2)/.003, .00002/, ZOPP(2)/.02, .006/
C   RATES OF NITROGEN EXCRETION PER BIOMASS UNIT:
C   1 , AEXCN(2)/20. , 34. /, ZEXCN /.03/
C   INGESTED RATION PER BIOMASS UNIT:
C   2 , ARTN(2)/2.4 , 3.9/, ZRTN /.007/
C   GRAZK IS THE EXPONENT IN THE IVLEV GRAZING EQUATION: 1 - EXP(K*PHYTO)
C   3 , GKAZK/ -5.776/
C   "SEASON" SPECIFIES AUTUMN (1), WINTER (2), OR ZERO (0) BIOMASSES AND RATES
C   INTEGER SEASON /2/
C   DATA IL/0/
C
C   REAL LTLIM,MXLIM
C   INTEGER DAY,GRID
C   INTEGER LAB(1,6)/'PRPN','MGC','L/DA','Y ',' ',' ' /
C   COMMON /CNTPL/MXGRID,ICUT,MX,NY,NZ,DX,DY,DZ,DT,DAY,HOUR,TEMP(100 )
C   1 /PHYT/GMAX(100 ),LTLIM(100 ),MXLIM(100 ),LSIGN(100 ),GP(100 )
C   2 /CNVKT/ C1NP,C1PP,C1STP
C   3 /VALUES/ P(100 ), NH4(100 ),NU2NO3(100 ),PO4(100 ),SI(100 )
C   4 /CHANGE/DP(100 ),DNH4(100 ),DNOX(100 ),DPO4(100 ),DSI(100 )
C   MXGRID=NX*NY*NZ
C   FROM MAIN
C
C   CALL PHYTO
C   IF((1.NE.0)G) TO 15
C   IL=1
C   IF(SEASON.GT.0)GO TO 10
C   SEASON=1
C   ZOPP(1)=0.
C   ANCH(1)=0.
10  ZEXCN =ZEXCN * ZOPP(SEASON)
C   ZRTN =ZRTN * ZOPP(SEASON)
C   ANEXCN=ZEXCN(SEASON) * ANCH(SEASON)
C   ANRTN =ARTN (SEASON) * ANCH(SEASON)
C   EXCRETION OF OTHER NUTRIENTS ACCORDING TO RATIO VS. N
C   ZOPP EXCN= 11:0.5:1 AND ANCHVY EXCN= 5:0.22:1 ( N : SI : P )
C   ZEXCP=ZEXCN/11.0
C   ZEXCSI=ZEXCP*0.5
C   ANEXCP=ANEXCN/5.0
C   ANEXSI=ANEXCP*0.22
15  CONTINUE
C   COMPUTE RATES OF CHANGE PER HOUR FOR STATE VARIABLES
C   DO 20 GRID=1,MXGRID
C   IF(P(1,GRID).GT.0.)GO TO 16

```

PER L

UGATN/L

MG C/HR

L/MG C

UGAT/L/H

MGC/L/HR

N:P=11

SI:P=0.5

N:P=5.0

SI:P=.22

```

XLMZ=0.
XLIMA=0.
RATIN=0.
FILT=0.
14  GP(GRID)=0.
    PNET=0.
    GO TO 1A
16  XLMZ=1.0-EXP(GRAZX*(P(GRID)-ZPO))
C   FEEDING THRESHOLDS FOR ZUPL (ZPO) AND ANCHURY (APO)
    DATA ZPO,APO/0.04, 0.24/
    IF(XLMZ.LT.0.0) XLMZ=0.
    XLIMA=1.0-EXP(GRAZX*(P(GRID)-APO))
    IF(XLIMA.LT.0.0) XLIMA=0.
    RATIN=ZRTN*XLMZ + ANRTN*XLIMA
    FILT=RATIN/P(GRID)
    CHG=GP(GRID)-FILT
    IF(CHG.LE.0.) GO TO 14
    TERM=EXP(CHG)-1.0
    GP(GRID)=P(GRID)*TERM
    PNET=0.
    IF(CHG.NE.0.) PNET=GP(GRID)*P(GRID)*TERM/CHG
18  DNH4(GRID)= -PNET/C$ND + ZEXCN*XLMZ + ANEXCN*XLIMA
    DPO4(GRID)= -PNET/C$PP + ZEXCP*XLMZ + ANEXCP*XLIMA
    DSI(GRID)= -PNET/C$IP + ZEXSI*XLMZ + ANEXSI*XLIMA
20  CONTINUE
    RETURN
    END

```

1/HR

UGAT/L
UGAT/L

```

SUBROUTINE PHYTO
IMPLICIT REAL (I,K,N)
INTEGER GRID,I,K,DAY,TODAY/D/,LIM(3)/'N','P','S'/
1,NX,NY,NZ,NXNY,IOUT
REAL EXCOEF(100),LTLIM,MXLIM
DIMENSION OUTEX( 70),OUTLT( 70),OUTMX( 70),OUTGP( 70),LSOUT( 70)
EQUIVALENCE (OUTEX(1),EXCOEF(1)),(OUTLT(1),LTLIM(1)),
1 (OUTMX(1),MXLIM(1)),(OUTGP(1),GP(1)),(LSOUT(1),LSIGN(1))
COMMON /CNTRL/MXGRID,IOUT,NX,NY,NZ,DX,DY,DZ,UT,DAY,HOURL,T(100) T=TEMP
1 /PHYT/GMAX(100),LTLIM(100),MXLIM(100),LSIGN(100),GP(100)
2 /CNVRT/ C$NP,C$PP,C$SIP
3 /VALUES/ P(100), NH(100),NN2NO3(100),PO(100),SI(100)
DATA IOPT/150./, F/.5/, RADN/300./, KO/.025/, KSN/1.5/,
1 KSP/.25/, KSSI/.75/
C NOT ALL STEPS NECESSARY IN EACH ITERATION --
C TEMP - DEPENDENT GMAX DETERMINED ONE TIME FOR CONSTANT TEMP FIELD
IF(TODAY.NE.O)GO TO 20
NXNY=NX*NY
C IOPT SHOULD BE DETERMINED FOR THE WATER COLUMN AND SEASON, ETC.
DATA OTT/4.166667E-2/ DAYS/HR
DO 10 GRID=1,MXGRID
GMAX(GRID)=EXP(0.063*T(GRID)-0.16) EPPLEY
10 GMAX(GRID)=GMAX(GRID) * OTT / HR
C COMPUTE NUTRIENT CONVERSION FACTORS FROM RATIO BY ATOMS: C:N:S:P
C (UG-AT NUTR)/(1.272 MGC PER 106 UG-AT C) = UG-AT/MG C
C$NP =1.272/C$NP MGC/UGAT
C$PP =1.272/C$PP
C$SIP=1.272/C$SIP
20 CONTINUE
C
C DETERMINE LTLIM ONE TIME DAILY
IF(DAY.FQ.TODAY)GO TO 50
C TODAY => DAY ONLY DURING FIRST TIME-STEP OF EACH DAY
TODAY=DAY
TERM=2.72*F
C LTLIM IS COMPUTED IN SEQUENCE FOR GRIDS DOWN THRU THE WATER COLUMN
DO 30 I=1,NX
DO 30 J=1,NY
J1=(J-1)*NX
I1=RADN
DO 30 K=1,NZ
C CONVERT FROM 3-DIM SUBSCRIPTS TO LINEAR LOCATIONS
GRID=I+ J1+ (K-1)*NXNY
EXCOEF(GRID)=KO+0.2514*P(GRID)+0.5047*(P(GRID)**0.666667) RILEY
C RILEY EQN. ORIG.: .0088(CHL UG/L) + .054(CHL**.67) ASSUMING C:CHL = 35.
C KO BASED ON 6 SAMPLES FROM PERU, = 0.025 1/M

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```

KZ=EXCDEF(GRID)*DZ
TERM1=11/IOPT
EKZ=EXP(-KZ)
TERM2=TERM1*EKZ
LTLIM(GRID)=TERM/KZ*(EXP(-TERM2)-EXP(-TERM1))
IF(I1.GE.10PT)LTLIM(GRID)=LTLIM(GRID)*0.85
I1=I1*EKZ
30 CONTINUE
50 CONTINUE
C
C NUTRIENT CALCULATIONS MAY NOT NEED TO BE MADE HOURLY, ...
C NUTRIENT LIMITATION -- 3 NUTRIENTS
C NH4 PREFERENCE MAY BE INCLUDED WITH UPTAKE SECTION
DO 100 GRID=1,MXGRID
  NTOT=NH4(GRID)+NU2NO3(GRID)
  NLIM = NTOT / (KSN + NTOT)
  PLIM = PO4(GRID)/(KSP + PO4(GRID))
  SILIM = SI(GRID)/(KSSI+ SI(GRID))
C MXLIM IS THE LIMITATION FACTOR OF THE MOST LIMITING NUTRIENT
  MXLIM(GRID)=AMIN1(NLIM,PLIM,SILIM)
C WALSH METHOD OF IDENTIFYING MXLIM: VS. 16:10:1 N:SI:P
C IF(PO4(GRID).GT.0.)NRATIO=(NTOT /PO4(GRID))/16.0
C IF(PO4(GRID).GT.0.)SIRATIO=( SI(GRID)/PO4(GRID))/10.0
C MXLIM(GRID)=PLIM
C IF(NRATIO.LT.1.0)MXLIM(GRID)=NLIM
C IF(SIRATIO.LT.NRATIO)MXLIM(GRID)=SILIM
C LSIGN IDENTIFIES WHICH NUTRIENT IS NOW LIMITING
  LSIGN(GRID)=LIM(1)
  IF(MXLIM(GRID).EQ.PLIM )LSIGN(GRID)=LIM(2)
  IF(MXLIM(GRID).EQ.SILIM )LSIGN(GRID)=LIM(3)
  GP(GRID)=GMAX(GRID)*LTLIM(GRID)*MXLIM(GRID)
100 CONTINUE
  IF(IOUT.EQ.1)
105 1WRITE(6,105) OUTEX,OUTLT,OUTMX,OUTGP,LSOUT
      1FORMAT('1 K'/ 7(10X,10F7.4/), '0 LT'/ 7(10X,10F7.4/),
      1 '0 MAX'/ 7(10X,10F7.4/), '0 GP'/ 7(10X,10F7.4/),
      1 '0NUTR'/ 7(10X,10A4 /))
      RETURN
      END

```

KREMER

```

SUBROUTINE PROFIL
  INTEGER LABPC(7)/'FITO','OPLA','NCTO','N ','MG C','/L ','/'
1  , LABCHL(7)/'CHL','ROFI','LA ','UG ','CHL','/L ','/'
2  , LABCI4(7)/'PROD','UCCI','ON ','MG ','C/M3','/DIA','/'
3  , LABNH4(7)/'AMMO','NIAC','O ','UG-A','T/L ','/'
4  , LABNOX(7)/'NITR','ATOS','Y N','ITRI','TOS ','UG-','AT/L/'
5  , LABPO4(7)/'FOSF','ATOS',' ','UG-A','T/L ','/'
6  , LABSIL(7)/'SILI','CATO','S ','UG-A','T/L ','/'
7  , LABCCL(7)/'ASSI','MILA','TION','MG ','C/MG','CHL','/DIA/'
8  , LABDPP(7)/'PROD','UCCI','ON C','OMMU','NIDA','D C','M3/D/'
  INTEGER DAY
  REAL LTLIM, MXLIM, NH4, NO2NO3
1, CHL(100 ), AR(100 )/100 *0./, PN(100 )
  COMMON /CNTRL/MXGRID, IOUT, NX, NY, NZ, DX, DY, DZ, DT, DAY, HOUR, TEMP(100 )
1 /PHYT/GMAX(100 ), LTLIM(100 ), MXLIM(100 ), LSIGN(100 ), GP(100 )
2 /CNVRT/ C$NP, C$PP, C$SIP
3 /VALUES/ P(100 ), NH4(100 ), NO2NO3(100 ), PO4(100 ), SI(100 )
4 /CHANGE/DP(100 ), DNH4(100 ), DNOX(100 ), DPO4(100 ), DSI(100 )

C
C
C   MXGRID=70
C
C   PRINT OUT FINAL VALUES AND RATES
C   DO 100 I=1, MXGRID
C   CHLOROPHYLL DISTRIBUTION
C   DATA C$CHL/35.0/
20  CHL(I)=P(I)/C$CHL *1000.
C   NET PHYTO. PRODUCTIVITY (MG C/M3.DAY; =C-14)
30  PN(I)=P(I)*1000.*(EXP(24.*GP(I))-1.0)
C   ASSIMILATION RATIO -- UG C/UG CHL/DAY
40  IF(CHL(I).GT.0.)AR(I)=PN(I)/CHL(I) *24.
C   NET COMMUNITY PRODUCTION -- PRODUCTIVITY + GRAZING
50  DP(I)= 1000. * EXP(10P(I)*24.0)
100 CONTINUE
  WRITE(6,200)LABCHL, (CHL(I), I=1, MXGRID)
  WRITE(6,200)LABCI4, (PN(I), I=1, MXGRID)
  WRITE(6,200)LABCCL, (AR(I), I=1, MXGRID)
  WRITE(6,200)LABDPP, (DP(I), I=1, MXGRID)
  RETURN
200 FORMAT(1H1,T41,7A4///'O',8X,'_',1X,99(' ')/7X,' O |',T111,'|'/
.10X,'|',10(F8.3,2X),T111,'|'/
.10X,'|',T111,'|'/ ' P 10_|',T111,'|'/10X,'|',T111,'|'/
. ' R',7X,'|',10(F8.3,2X),T111,'|'/10X,'|',T111,'|'/ ' O 20_|',
.T111,'|'/10X,'|',T111,'|'/ ' F',7X,'|',10(F8.3,2X),T111,'|'/10X,
.'|',T111,'|'/ ' U 30_|',T111,'|'/10X,'|',T111,'|'/ ' N',7X,'|',
.10(F8.3,2X),T111,'|'/10X,'|',T111,'|'/ ' D 40_|',T111,'|'/10X,

```

T	X-GRID	1									
			14.000	15.000	16.000	17.000	18.000	19.000	19.000	19.000	19.000
			14.000	14.000	15.000	16.000	17.000	18.000	18.000	18.000	18.000
			14.000	14.000	14.000	15.000	15.000	16.000	16.000	16.000	16.000
			14.000	14.000	14.000	14.000	15.000	15.000	15.000	15.000	15.000
			14.000	14.000	14.000	14.000	14.000	14.000	14.000	14.000	14.000
			13.000	13.000	14.000	14.000	14.000	14.000	14.000	14.000	14.000
			13.000	13.000	13.000	13.000	13.000	13.000	13.000	13.000	13.000
			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

VY	X-GRID	1									
			540.000	1224.000	1404.000	1440.000	1440.000	1440.000	1440.000	1440.000	1440.000
			144.000	324.000	396.000	432.000	432.000	432.000	432.000	432.000	432.000
			-144.000	-324.000	-360.000	-360.000	-360.000	-360.000	-360.000	-360.000	-360.000
			-144.000	-324.000	-360.000	-360.000	-360.000	-360.000	-360.000	-360.000	-360.000
			-144.000	-324.000	-360.000	-360.000	-360.000	-360.000	-360.000	-360.000	-360.000
			-252.000	-396.000	-324.000	-360.000	-360.000	-360.000	-360.000	-360.000	-360.000
			0.0	-140.000	-396.000	-432.000	-432.000	-432.000	-432.000	-432.000	-432.000

VZ	X-GRID	1									
			-0.540	-0.144	-0.036	0.0	0.0	0.0	0.0	0.0	0.0
			-1.224	-0.324	-0.108	0.0	0.0	0.0	0.0	0.0	0.0
			-1.224	-0.324	-0.144	0.0	0.0	0.0	0.0	0.0	0.0
			-0.936	-0.252	-0.144	0.0	0.0	0.0	0.0	0.0	0.0
			-0.648	-0.180	-0.144	0.0	0.0	0.0	0.0	0.0	0.0
			-0.252	-0.252	-0.108	0.0	0.0	0.0	0.0	0.0	0.0
			0.0	-0.180	-0.036	0.0	0.0	0.0	0.0	0.0	0.0

INPUT DATA READ FROM SET 5, EFFECTIVE START-UP ON DAY 1


```

SUBROUTINE STDYST
  INTEGER DAY
  REAL CHG(60)/60*0./
  INTEGER GRID
  COMMON /VALUES/VAL(500 )
  1 /CNTRL/MXGRID,IOUT,NX,NY,NZ,DX,DY,DZ,DT,DAY,HOUR,T(100 )
  DATA SUM20/10000./
  DATA STABLE/0.001 /
  DATA I/O/
  I=I+1
  SUM=0.
  DO 10 GRID=1,20
    SUM=SUM+VAL (GRID)
10  CONTINUE
    CHANGE=(SUM20-SUM)/SUM
    SUM20=SUM
    CHG(I)=CHANGE
    IF(DAY.EQ.51)WRITE(6,30)CHG
    IF(ABS(CHANGE).GT.STABLE)RETURN
    WRITE(6,20)CHANGE, DAY, HOUR
20  FORMAT('O  STEADY-STATE CRITERION MET, RUN TERMINATED ./
1  'O  TOTAL CHANGE IN TOP 20 GRIDS =',E15.5,' OF PREVIOUS TOTAL'/
1  'O  TIME AT TERMINATION: ', 15,F5.1)
    WRITE(6,30)CHG
30  FORMAT('O  SEQUENCE OF CHANGE VALUES LEADING TO STEADY STATE: '//
1  (1X,10E12.4))
    DATA IOSET/6/
    IF(IOSET.NE.6)WRITE(10SET,915)DAY,VAL
    WRITE(6,916)IOSET
915  FORMAT(15/(10F8.5))
916  FORMAT('O ==> OUTPUT INITIAL CONDITIONS TO SET',15/)
    CALL PROFIL
    STOP 1
  END

```

```
.|',T111 '|/' '|,7X,'|',10(F8.3,2X),T111,'|'/10X,'|',T111,'|'/
.' 0 50_|',T111,'|'/10X,'|',T111,'|'/ 'A',7X,'|',10(F8.3,2X),
.T111,'|'/10X,'|',T111,'|'/ '0 60_|',T111,'|'/10X,'|',T111,'|'/
.10X,'|',10(F8.3,2X),T111,'|'/10X,'|',T111,'|'/ (M) 70_|',T111,
.'|'/ 3(10X,'|',T111,'|'/),7X,'80_|',T111,'|'/ 3(10X,'|',T111,'|'/)
.,7X,'90_|',T111,'|'/3(10X,'|',T111,'|'/),6X,'100_|',99(' '),'|'/
.11X,10(9X,'|')/19X,'10',8X,'20',3X,'30',8X,'40',8X,'50',8X,'60',3X
.,'70',8X,'80',8X,'90',8X,'100'//T44,'DISTANCIA DE LA COSTA (KM)')
END
```

DAY	1	1.00	CONCENTRATION PPL	X GRID	2						
	0.041	0.041	0.040	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.041	0.041	0.041	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.041	0.041	0.039	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	0.040	0.040	0.039	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	0.040	0.040	0.039	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	0.039	0.040	0.039	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	0.010	0.039	0.039	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010

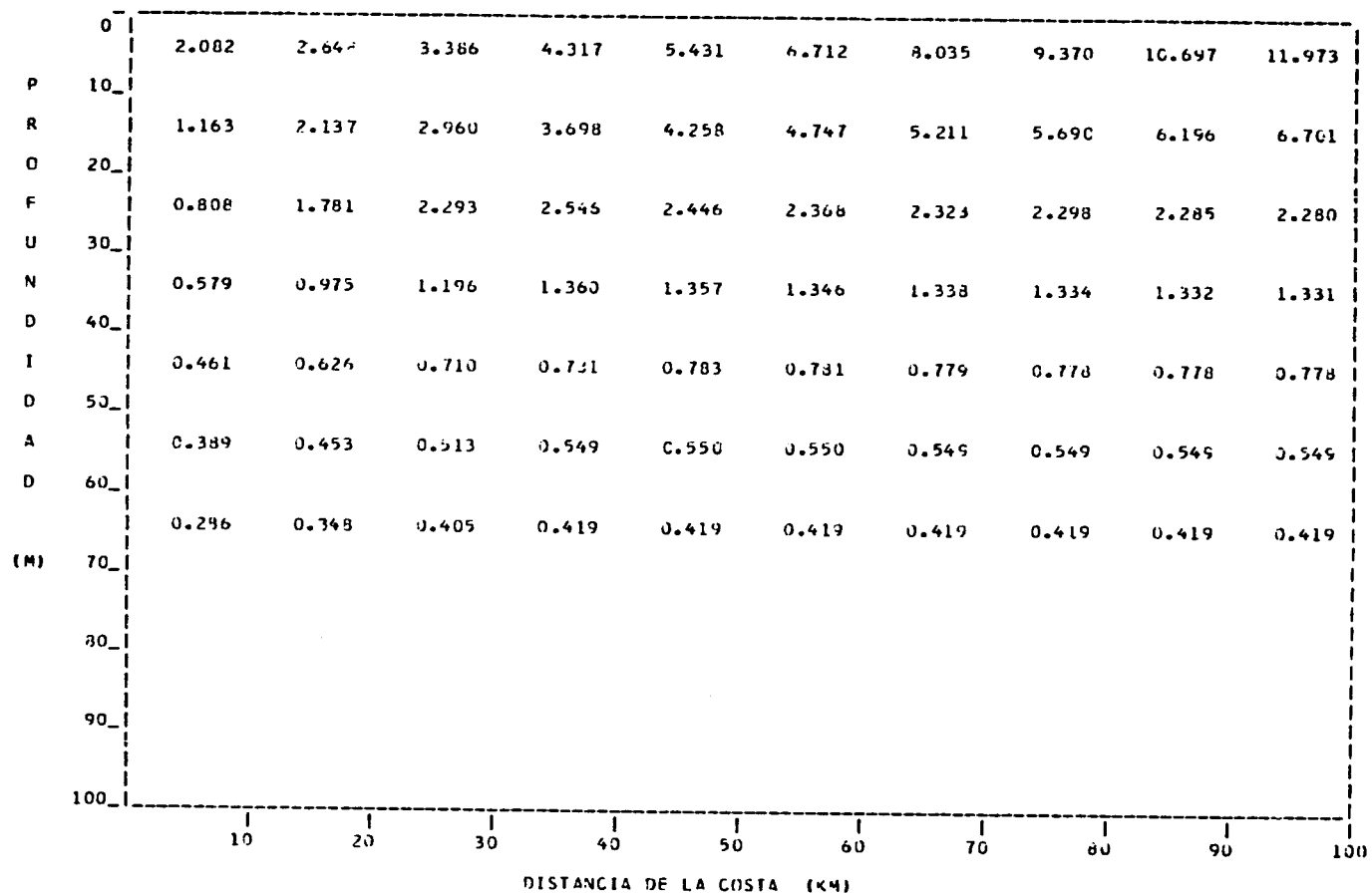
DAY	1	1.00	CONCENTRATION NH4	X GRID	2						
	0.493	0.493	0.492	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	0.487	0.487	0.486	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.500
	0.492	0.492	0.492	0.496	0.496	0.496	0.496	0.496	0.496	0.496	0.496
	0.496	0.496	0.496	0.496	0.496	0.496	0.496	0.496	0.496	0.496	0.496
	0.498	0.498	0.498	0.497	0.497	0.497	0.497	0.497	0.497	0.497	0.497
	0.499	0.499	0.499	0.498	0.498	0.498	0.498	0.498	0.498	0.498	0.498
	0.500	0.500	0.500	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499

DAY	1	1.00	CONCENTRATION NOX	X GRID	2						
	1.184	0.808	0.705	0.671	0.671	0.671	0.671	0.671	0.671	0.671	0.671
	10.531	10.081	9.973	9.919	9.919	9.919	9.919	9.919	9.919	9.919	9.919
	15.612	15.162	15.072	15.000	15.000	15.000	15.000	15.000	15.000	15.000	15.000
	20.468	20.126	20.072	20.000	20.000	20.000	20.000	20.000	20.000	20.000	20.000
	25.518	25.144	25.115	25.000	25.000	25.000	25.000	25.000	25.000	25.000	25.000
	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000
	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000	33.000

DAY	1	1.00	CONCENTRATION PO4	X GRID	2						
	0.428	0.413	0.408	0.407	0.407	0.407	0.407	0.407	0.407	0.407	0.407
	0.848	0.812	0.803	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800
	1.248	1.212	1.205	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
	1.637	1.610	1.606	1.600	1.600	1.600	1.600	1.600	1.600	1.600	1.600
	2.032	2.009	2.007	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500
	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500	2.500

DAY	1	1.00	CONCENTRATION SI	X GRID	2						
	3.068	3.028	3.017	3.018	3.018	3.018	3.018	3.018	3.018	3.018	3.018
	4.395	4.125	4.059	4.036	4.036	4.036	4.036	4.036	4.036	4.036	4.036
	7.362	7.092	7.038	6.997	6.997	6.997	6.997	6.997	6.997	6.997	6.997
	10.279	10.073	10.041	9.997	9.997	9.997	9.997	9.997	9.997	9.997	9.997
	13.777	13.215	13.172	12.998	12.998	12.998	12.998	12.998	12.998	12.998	12.998
	25.000	25.000	25.000	24.999	24.999	24.999	24.999	24.999	24.999	24.999	24.999
	25.000	25.000	25.000	24.999	24.999	24.999	24.999	24.999	24.999	24.999	24.999

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Objectives of the economic study were three:

1. planning with the staff of the Instituto del Mar, Peru (IMARPE) for an economic analysis of issues of interest, using available data
2. reviewing fishery economic issues in the Ilo, Peru, area with special reference to (a.) artisanal fisheries, and (b.) the production, distribution, and marketing of fish for human consumption
3. exploring the possibility of constructing an economic model capable of interfacing with the ecosystem model to be developed by Scott Nixon and James Kremer.

These general objectives were achieved, though each to a different extent. As should become clear in the next section, my visit focused on objectives 1. and 2. Constructing the model in 3. probably is not feasible in the near future due to the short time allocated and lack of appropriate data on the food fishery.

Results

Following discussions with persons in the Ministry of Fisheries and related entities (such as EPSEP and Pesca Peru), with artisan fishermen and the IMARPE laboratory staff in Ilo, Dr. W. Macedo and I drew up a tentative research program for his office.

The tentative program consists of a short-term and a long-term program of economic research. The short-term program was the major focus of concern, and although developed in some detail it still needs refinement as well as an indication of support by IMARPE. It calls for a study of the artisanal fishery around the port of Ilo (including Villa Villa and Meca) with the objective of making recommendations for the development of the fishery. (A tentative outline of such a study is presented in table 1.) Much of the information necessary for the above study is contained in an existing paper by A. Pastor and N. Galarza, Estudio Preliminar Sobre La Pesca Artesanal En El Puerto De Ilo, IMARPE, 1974. Additional information was gathered during our recent visit to the Ilo area.

However, information on the costs and earnings of capital, and on the earnings and characteristics of the fishermen has not yet been collected. Since this information is a critical part of the study, we believe its collection should begin immediately. The first step necessary for collecting such data is to develop an appropriate form for the field staff to use. Examples of such forms were left at IMARPE. The appropriate form will be developed by the IMARPE economist in consultation with the Ilo field staff, who will be responsible for collecting the data. Development of these forms can begin at once without adding much of a burden on IMARPE's staff.

Table 1. A tentative outline of an economic study of the Ilo artisanal fishery.

- I. Introduction
- II. Description of the fishery
 - A. The resource (magnitude, location, species, etc.)
 - B. The harvesting sector
 - 1. Output and prices (past and present)
 - 2. Capital inputs
 - a. description of gear, techniques, and the enterprises' operations
 - b. costs and earnings of the enterprises
 - c. supporting infrastructure (repair and construction,
 - 3. Labor inputs
 - a. description of skills, education, ethnic and social status, and alternative economic opportunities
 - b. earnings
 - c. supporting infrastructure (schools, housing, hospitals, etc.)
 - C. Processing
 - D. Distribution
 - E. Marketing
- III. Prospects for Development
 - A. Resource potential
 - B. Harvesting sector
 - 1. New vessels, gear and techniques
 - 2. Fishermen training
 - 3. Supporting infrastructure development
 - C. Processing
 - D. Distribution
 - E. Marketing
- IV. Recommendations for development and future research

Data collection will be for an appropriate sample size and composition. For example, 25 vessels and their crews may suffice; however, other considerations may call for this number to be reduced or expanded. The vessels in the sample should be chosen to capture a variety of vessel sizes, gear types, major species caught, locations of operation, etc. The costs and earnings of these enterprises will be monitored for a full fishing season and may be collected at the end of every fishing trip along with the current collections of landings quantity, composition, and value data.

The parts of the study concerning processing, distribution and marketing probably will be of a cursory nature for two reasons:

1. processing, distribution, and marketing are more naturally the concern of EPSEP, the processing, distribution, and marketing arm of the Fisheries Ministry, and 2. whereas IMARPE routinely collects catch statistics and therefore has established close links with the harvesting sector, it would require a substantial increase in personnel to monitor the other activities. Of course, IMARPE personnel would be remiss if they did not attempt to obtain as much of this information as possible from EPSEP. However, any major study of processing, distribution and marketing should be carried out by EPSEP or another branch of the Fisheries Ministry, or at least postponed until IMARPE develops the capability to thoroughly study these issues.

A logical question at this point is how will this study meet its objectives, i.e., what are some recommendations for the fishery's development likely to emerge from the study? From the analysis of costs and earnings data on existing and new forms of capital, the study will likely prescribe any beneficial changes in the types of vessels, gear and techniques to be used. The study will propose actions to resolve any problems of financing vessels and gear, of repairing and constructing vessels, of supplying gear and other equipment, etc. Similarly with labor, the study will likely assess the manpower needs for developing the fishery, i.e., the number of fishermen and the types of skills requires, and propose means of providing this manpower, i.e., the wage level, training, housing, schools and medical facilities needed. In the areas of processing, distribution and marketing, the study will at least identify major problem areas, and suggest the necessary research to resolve these problems.

The second, or long-term, part of the research program is only speculative. It is not clear at this time what IMARPE's role will be in fishery economic research in the distant future. What is clear, however--or at least becoming more evident to a number of Peruvian researchers and administrators--is that much more economic research is required for the proper development and management of the exploitation of Peru's fishery resources. Inter alia, the monitoring and analysis of costs and earnings in the industry will be an important part of such research. Therefore, in the long run IMARPE may wish to develop the capability to routinely collect and analyze costs and earnings data. If so, the Ilo research program can be regarded as a first step in developing such a capability.

Role of AID/ICMRD in Peruvian Fishery Economic Research

While there appears to be a substantial interest in expanding Peru's fishery economic research capabilities, no single entity at this time is engaged in developing a comprehensive economic research program. Just how, when and where such a program will be developed is not clear. Given that such a program will be developed in the future, however, some thought and commitment should be made soon regarding training Peruvian economists and outlining a comprehensive research program. AID could play a meaningful role by funding the training of Peruvian fishery economists at U.S. universities. Although FAO has played a major role in economic research in the past, AID, it seems, can fill a valuable niche by providing skilled advisors to develop the research program and to conduct some of the research.

Should the above scenario be realized, the implications for ICMRD and the Department of Resource Economics are obvious. However, in the very near future there exists a need for continued resource economics involvement. If the above study is to be carried out, more refinement of its exact contents is necessary. I am sure further analytical assistance will be desired by IMARPE's economist. Therefore, a request for additional resource economics involvement is likely to be forthcoming in the near future.

References

- DiToro, D.M., D.J. O'Connors and R.V. Thomann. 1971. A dynamic model of phytoplankton populations in the Sacramento-San Joaquin delta. Adv. in Chem. Series 106: 131-180.
- Eppley, R.W. 1972. Temperature and phytoplankton growth in the sea. Fish. Bull. 70(4): 1063-1085.
- Frost, B.W. 1975. A threshold feeding behavior in Calanus pacificus. Limnology & Oceanography 20(2): 263-266.
- Ivlev, V.S. 1945. The biological productivity of waters. Uspekhi Sovrem. Biol. 19: 98-120.
- Mullin, M.M., E.F. Stewart, F.J. Fuglister. 1975. Ingestion of planktonic grazers as a function of concentration of food. Limnology & Oceanography 20(2): 259-262.
- Nixon, S.W. and J.N. Kremer. Narragansett Bay--The development of a composite simulation model for a New England estuary in models as ecological tools: Theory and case histories. C. Hall and J. Day (eds.), Wiley-Interscience (in press).
- Riley, G.A. 1956. Oceanography of Long Island Sound 1952-54. II. Physical Oceanography. Bull. Bingham Ocean. Coll. 15: 15-46.
- Steele, J.H. 1962. Environmental control of photosynthesis in the sea. Limnology & Oceanography 7: 137-150.
- Walsh, J.J. 1975. A spatial simulation model of the Peru upwelling. Deep Sea Res. 22: 201-236.

University of Rhode Island - Instituto del Mar Project Schedule

Jon G. Sutinen

<u>Time</u> <u>(Days)</u>	<u>Dates</u> <u>(1975)</u>	<u>Place</u>	
18	20 Jan-7 Feb	Peru	Site visit to assist Instituto del Mar personnel in planning economic analysis; review fishery economic issues in the Ilo area with reference to artisanal fisheries and to production, distribution and marketing of fish.

James N. Kremer

<u>Time</u> <u>(Days)</u>	<u>Dates</u> <u>(1975)</u>	<u>Place</u>	
17	1-17 Feb	R. I.	Preparation phase: review physical characteristics of study area and available biological data supplied by Instituto del Mar personnel; write computer program for physical circulation model.
22	18 Feb-11 Mar	Peru	Discuss circulation model; formulate and analyze basic conceptual phytoplankton model. Survey available data with preliminary hand calculations comparing theoretical formulations with observed data. Preliminary estimates of some parameters appropriate to the Peru system.
49	12 May-29 Apr	R. I.	Development of phytoplankton submodel as discussed in Peru; development of ecological model framework to complement PHYTO submodel, including herbivore (anchovy and zooplankton) grazing and excretion influences. Preliminary computer simulation runs and evaluation.
20	30 Apr-19 May	Peru	Analyze and evaluate final model formulations. Discuss suggested modifications in the model and research and field observations. Discuss with Instituto del Mar personnel the technical details of the model methods. Present lecture on ecosystem model.
4	20-23 May	R. I.	Preparation of final report

Scott W. Nixon, Assistant Professor at URI. Ten days, 7-16 May, in Peru, consultation and discussion with Dr. Guillen of Instituto del Mar on modeling and ecosystem analysis. Present lecture on role of modeling in ecosystem research. Seven days, 17-23 May, in R. I. assisting in preparation of final report.