# GLOBAL OCEAN ECOSYSTEM DYNAMICS

## GLOBEC REPORT NO. 6

# NUMERICAL MODELING

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# NUMERICAL MODELING

## Report of the First Meeting of an International GLOBEC Working Group

Villefranche-sur-mer, France

July 12 - 14, 1993

# PREFACE

The international program on Global Ocean Ecosystem Dynamics (GLOBEC) is sponsored by the Scientific Committee on Oceanic Research (SCOR) with the co-sponsorship of the Intergovernment Oceanographic Commission, the International Council for the Exploration of the Sea and the North Pacific Marine Science Organization. GLOBEC is dedicated to understanding the effects of physical processes on predator-prey interactions and population dynamics of zooplankton and their relation to ocean ecosystems in the context of the global climate system and anthropogenic change.

The GLOBEC Core Program is being developed through a series of scientific working groups and regional planning effects. This report results from the fifth in the series of meetings of these groups leading to the development of an international Science Plan for GLOBEC. The Working Group on Development of an International Numerical Modeling Program met in Villefranche-sur-mer, France, July 12-14, 1993.

This meeting was chaired by Professor Allan Robinson to whom the international sponsors of GLOBEC wish to express their gratitude for his leadership.

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## REPORT OF THE INTERNATIONAL GLOBEC NUMERICAL MODELING WORKING GROUP MEETING,
### Villefranche, France, 12—14 July, 1993

The overall goal of International GLOBEC is "To understand the effects of physical processes on predator-prey interactions and population dynamics of zooplankton, and their relation to ocean ecosystems in the context of the global climate system and anthropogenic change." The terms of reference for the Numerical Modeling Working Group (NM-WG) are:

1. To assess the state-of-the-art of coupled biological-physical interdisciplinary models relevant to GLOBEC, to identify model developments critical to the achievement of GLOBEC objectives and actively to foster such developments. Issues include:

    a) scientific, mathematical and computational aspects of multiscale, interactive and nested models  
    b) the identification and explicit representation of essential biological and physical processes and interactions  
    c) the identification, over the hierarchy of scales, of essential subgrid-scale biological and physical processes and their representation via parameterization.

2. To unify the GLOBEC modeling and observational efforts, to specify data requirements for efficient model utilization and to initiate and coordinate research developments in advanced methodologies for interdisciplinary field estimation via data assimilation. Issues include:

    a) the specification and utilization of critical and efficient biological variables for use in modeling and in monitoring  
    b) the design of experiments and observational networks utilizing both sampling theoretic methods and observational system simulation experiments  
    c) the achievement with mesoscale resolution over large regions of realistic simulations and predictive capabilities.

3. To provide scientific and technical guidance and oversight for the requisite GLOBEC international interdisciplinary modeling program. Issues include:

    a) the acceleration of research progress through effective communications  
    b) resolution of critical technical issues through focused workshops and the synthesis of results and the dissemination of information through colloquia  
    c) model intercomparisons and validation and the encouragement of the development of modular model components and the exchange and sharing of software and data throughout the international community.

The first meeting of the NM-WG was held in Villefranche, France from 12—14 July, 1993 in order to discuss and define the scope of and approach to the modeling problem appropriate for GLOBEC.INT, and to develop and adopt the program of activities for the NM-WG. The initial scientific context for the meeting was set by presentation of individual viewpoints by each working group member. This was followed by plenary discussions on: i)processes and modeling issues organized by scales (small, meso, regional, coastal, large and global); numerical methods and data assimilation; observations, experiments and data sets; functional and logistical issues. A brief but substantive summary of these discussions is given by the terms of reference which resulted for the NM-WG and which are presented in the first paragraph above. There were also informational plenary briefings about other pertinent working groups and programs.

Three working groups were then formed.

1. *Observational and Modeling Variables*: Definition of quantities for assimilation and verification.
2. *Test Beds*: An observational and modeling system for ecosystem dynamics research and monitoring.
3. *Models and Methods*: Interdisciplinary data assimilation into nested multiscale models.

After the working group deliberations, a final plenary session met to review and adopt recommendations.

It is an interesting time in ocean science now that for the first time there exist the scientific and technical bases for understanding biological-physical interactions, and the dynamics, variabilities, forced responses and sensitivities of regional and global ecosystems. The tasks of the NM-WG are feasible but lie at the research frontier of interdisciplinary modeling. A concerted program is required to develop and apply new models and methods, and to relate such models to observations and experiments with the optimal choice of biological state variables and adequate representation of biological rate parameters. Data assimilation is of paramount importance and its effective and efficient implementation requires the simultaneous and synergetic acquisition of biological, chemical and physical data from a mix of *in situ* and remote sensors deployed on a variety of platforms arranged in optimally designed arrays. The magnitude and importance of these modeling tasks are such that success can only be achieved through international cooperation and GLOBEC.INT NM-WG should provide the mechanisms for the required activities and interactions.

The design, development and deployment of a coupled numerical model/observational system for ecosystem research and monitoring is necessary in order to achieve an understanding of, and to develop a predictive capability for, the global ecosystem. The system will be used for nowcasts, forecasts and realistic simulations. It should be generic, modular, portable and flexible with sophisticated and simple versions. The observational system must be multiplatform and multisensor. It will incorporate and integrate physical, biological and chemical measurements taken by *in situ* and remote sensors. The model component will be multiscale and interdisciplinary. The multiscale aspect will involve nesting of regions in larger scale domains with the possibility of two-way feedbacks and the coupling of coastal regions across the shelf-break to the open ocean. It will be capable of mesoscale resolution over large regions of critical biological/physical processes. Central to the system's functioning is data assimilation, i.e., the assimilation of matched physical, biological and chemical variables into the coupled interdisciplinary dynamical models. The field estimates obtained will be used for process studies, predicting the evolution of the ecosystems, and simulating the ecosystem dynamics and ecosystem change scenarios. Process studies will be carried out by balance of terms studies of physical and biological dynamical balances. Of particular importance are Observing System Simulation Experiments (OSSEs). Realistic simulations will be carried out and the four-dimensional multidisciplinary fields will then be used as "true" oceanic data for the design and evaluation of observational systems, experiments, and sampling schemes. This method, first developed in meteorology, is now used in physical oceanography. It should be of particular importance to the design, development and utilization of the coupled ecosystem model/observational system. Several deployments should be carried out during the course of GLOBEC.INT, initially with a research orientation and finally with a monitoring orientation.

The specific recommendations of the NM-WG are:

*Variables:*

1. Careful attention should be paid to specification of important GLOBEC relevant variables in the manner in which they are observed and used in model contexts. The variables Table A1 of this report should be expanded and improved with respect to its presentation of core variables, usage, units and errors expected in their determination.

2. Phytoplanton measurements should include appropriate size fractionated analyses with sufficient resolution to differentiate between phytoplankton and other food sources of the target zooplankton in each GLOBEC effort. For example at a minimum measurements of biomass and primary production for cells < 5 µm to delineate microzooplankton and copepod food resources is crucial for North Pacific versus North Atlantic intercomparisons. Coordination with JGOFS is desirable.

3. Maximal growth rates should be determined as a function of temperature under biochemically replete food conditions. These conditions should accurately reflect the nutritional sources for populations in the wild and be resolved to the extent that system shifts and adaptive variations are accounted for.

4. A working group should be established comprised of both observational and modeling investigators to develop methods for estimating both natural and predator based mortality in target populations.

*Test Bed: The Coupled Model/Observational System*

5. GLOBEC should initiate the design of an integrated observational sampling

and multidisciplinary assimilation system as a means of making significant progress in understanding the functioning of marine ecosystems. The aim should be to carry out at least two such exercises within the next 5—7 years.

6. Research should begin on designing and testing an ecosystem model that is structurally consistent with the biogeochemical and physical information that can be provided by remotely sensing instruments (deployed both *in situ* and on satellites).

7. Once potential study sites have been identified, Observational System Simulation Experiments should be carried out to determine the appropriate mix of sampling platforms and sensors and the optimum utilization of such platforms and sensors to aid in the selection of sites and in array design.

*Models and Methods:*

8. The international GLOBEC modeling program should invest resources in the development of multiscale nested models that are capable of interdisciplinary data assimilation.

9. International GLOBEC should sponsor a series of annual workshops that are focused on various topics in interdisciplinary modeling. It is anticipated that these workshops will also provide a forum for training students and researchers in interdisciplinary modeling.

10. The modeling programs developed within international GLOBEC should maintain strong ties with groups doing data collection and data analysis. This interaction could be fostered through workshops that bring together observationalists and modelers. Furthermore, GLOBEC should develop a strong policy on data management and data sharing.

# 1. INTRODUCTION

The overall goal of GLOBEC is "To understand the effects of physical processes on predator-prey interactions and population dynamics of zooplankton, and their relation to ocean ecosystems in the context of the global climate system and anthropogenic change." Numerical modeling is an essential element of the strategy to achieve this goal. The terms of reference for the Numerical Modeling Working Group (NM-WG) are:

1. To assess the state-of-the-art of coupled biological-physical interdisciplinary models relevant to GLOBEC, to identify model developments critical to the achievement of GLOBEC objectives and actively to foster such developments. Issues include:
    - a) scientific, mathematical and computational aspects of multiscale, interactive and nested models
    - b) the identification and explicit representation of essential biological and physical processes and interactions
    - c) the identification, over the hierarchy of scales, of essential subgrid-scale biological and physical processes and their representation via parameterization.
2. To unify the GLOBEC modeling and observational efforts, to specify data requirements for efficient model utilization and to initiate and coordinate research developments in advanced methodologies for interdisciplinary field estimation via data assimilation. Issues include:
    - a) the specification and utilization of critical and efficient biological variables for use in modeling and in monitoring
    - b) the design of experiments and observational networks utilizing both sampling theoretic methods and observational system simulation experiments
    - c) the achievement with mesoscale resolution over large regions of realistic simulations and predictive capabilities.
3. To provide scientific and technical guidance and oversight for the requisite GLOBEC international interdisciplinary modeling program. Issues include:
    - a) the acceleration of research progress through effective communications
    - b) resolution of critical technical issues through focused workshops and the synthesis of results and the dissemination of information through colloquia
    - c) model intercomparisons and validation and the encouragement of the development of modular model components and the exchange and sharing of software and data throughout the international community.

The specific purposes of the first NM-WG meeting were to (a) define the modeling problem, (b) define the approach to the problem, (c) develop and recommend a final term of reference for the NM-WG, (d) develop an overall plan for five years, and (e) develop specific plans for two years. The agenda of the meeting is included as Appendix C and is organized as follows. First the scientific context and background for the work at the meeting was supplied by introductory presentations from each member of the working group. Summaries of the individual presentations are given in Appendix B. Next, reports were delivered from two other GLOBEC.INT working groups (PDPV-WG and SOS-WG) that the NM-WG must coordinate with closely. Then a series of plenary scientific discussions were held to set the stage for the formation of the working groups. The working groups on scientific, technical, logistical and functional issues then met, wrote reports and made specific recommendations. The recommendations were discussed and adopted at a final plenary session.

This is a very interesting time in ocean science as the interdisciplinary problems introduced in the 1930s are only now tractable because of the progress made within the disciplines and the development of general methodologies. The GLOBEC modeling problem is fundamental and lies at the heart of such interdisciplinary ocean science. The program is concerned with ecosystem dynamics and population dynamics with particular emphasis on zooplankton and grazing, in the context of climate dynamics and global change. The parameter dependencies and the sensitivities of the forced response of the global ecosystem must be determined. Of paramount importance are physical, biological and chemical interactive processes and interdisciplinary modeling. Another issue is zooplankton-phytoplankton interactions and possible feedbacks to the climate system via biogeochemical fluxes.

Numerical models are natural vehicles for synthesis and application of knowledge to scientific and practical applications. Realistic process studies imply that realistic physical and biological structures be represented. Small-scale processes (subgrid-scale) must be adequately represented in their effect on explicitly resolved scales. Because our lack of knowledge is so great, it is now necessary to resolve mesoscale phenomena over large-scale regions and understand regional processes in their larger scale context. The global ecosystem problem involves regional modeling in basin and global contexts and global process modeling.

Scientific progress is possible in GLOBEC only if the modeling and experimental/observational programs are fully unified and integrated. Field estimates with the space-time resolutions and durations required can only be achieved by the melding of data and models, i.e., by data assimilation. A variety of sensors and platforms are implicated for process studies, nowcasts, forecasts and research monitoring. Thus to accomplish its goals, GLOBEC will have to use multiscale nested models with data assimilation of physical, biological and chemical variables. This poses novel methodological and scientific issues shared with the community generally which lie at the very frontier of interdisciplinary and multidisciplinary ocean science.

# 2. SCIENTIFIC AND TECHNICAL ISSUES

## 2.1 Process and Modeling Discussions

### 2.1.1 Small Scale

Physical structures and phenomena of interest include fronts, frontal processes, turbulence and exchange across the base of the mixed layer. The extent to which Lagrangian trajectories influence biological and chemical variability must also be better understood. Large eddy simulation is an important approach for process studies of this type which could lead to better parameterization of subgrid-scale processes.

Biological processes of interest span many trophic levels. The photosynthetic action spectra of primary producers are of fundamental importance. The modification of the surface ocean inherent optical properties through self-shading must be taken into account, particularly during bloom conditions. Heterotrophic grazing is largely controlled by contact frequency with food particles. Whether the grazed material sinks or is recycled, and the pathway of its remineralization has important effects on the functioning of ecosystems. Zooplankton behavior is of considerable interest, including active vertical migration in current shear and swarming processes. The most important question GLOBEC must address with regard to these processes is how they control species succession and food-web structure.

Relevant forcing functions include the heat, salt and momentum fluxes across the ocean surface and how they effect mixed layer behavior. The dynamics of the bottom boundary layer including resuspension processes may also be important in some instances. In terms of climate change, both wind and radiative forcing must be considered.

*Synthesis:*

One challenge of research conducted at this scale is to relate information about the individual organism to the population. This will permit assessment of what phenomena can be successfully parameterized and how to do so. Indeed, it is necessary to consider a hierarchy of parameterizations, e.g., to combine populations into various groups and to devise optimal concentration fields (space-time functions) for model variables. Because of the global nature of the program, there was general agreement that research on small-scale processes must be justified in terms of their importance at larger scales.

### 2.1.2 Mesoscale, Regional and Coastal

Issues of interest include deformation and decay of the thermocline and coastal interactions. The importance of mesoscale processes over large regions must be assessed. For now it is essential to resolve this scale; perhaps in the future it may be possible to effectively parameterize mesoscale effects. Relevant processes include perturbation of the thermocline by eddy formation and dynamics, submesoscale "hotspots" induced by mesoscale upwelling, and water column interactions (surface boundary layer—interior—bottom boundary layer). Coastal processes of interest include shelf-break fronts and tidally induced features.

Important forcing functions include wind and buoyancy driven transports, tidal rectification and seasonal effects. Inputs of biological and chemical constituents from the atmosphere, rivers and bottom boundary layer must be considered.

Synthesis:

The fundamental interconnections of physics and biology in this context are (a) physical structures and turbulence influencing energetics and transports of the organisms and (b) temperature controlling biological rate processes. There was a consensus that a regional approach with mesoscale resolution will be the best way to build the large-scale answers GLOBEC is searching for. Of course different regions will have different biological simplifications and conceptualizations. GLOBEC must face the challenge of developing global understanding from regional studies.

### 2.1.3 Large and Global Scale

Accurate representation of Ekman pumping is essential in large-scale modeling, as this represents a main driving mechanism for the major current systems. The role of mesoscale eddies, which are unresolved in most large-scale models, must be understood in terms of the general circulation and their biological impact. Equatorial waves, e.g., Legekis, also result in significant physical and biological variability in equatorial regions.

Seasonal cycles of phytoplankton and zooplankton populations are of considerable interest. The level of complexity required in globally robust models must be ascertained. An issue specific to large-scale models in this regard is biogeography. Large-scale representation of processes such as zooplankton behavior and remineralization of nutrients are also considered essential.

Important forcing functions for these systems are light and clouds from above and deep nutrients and export flux below. The question of iron limitation is being actively pursued. How these various processes cause changes in trophic structure and match-mismatch is a fundamental issue.

*Synthesis:*

There is a sense that basin and global scale modeling is in some ways premature because potentially important mesoscale processes have as yet been unresolved in such efforts. Only after such processes have been understood will it be possible to coarsen the resolution of global models and include mesoscale parameterizations.

## 2.2 Numerical Methods and Data Assimilation

Conceptual issues of interest include boundary conditions, parameterization, the use of nested models, and the representation of population structure in interdisciplinary models. Success in dealing with these problems hinges on overcoming technical issues of resolution $(x,y,z,t)$, implementation of boundary conditions, the construction of nested models, and preventing forward diffusion in population structure. This will require the commitment of substantial resources, including computers, personnel, data sets, instrumentation and high levels of funding.

The assimilation of data into interdisciplinary models is a novel area in which GLOBEC will make important contributions. Acquiring the necessary data sets for ecosystem updates via data assimilation is of primary importance. The use of adjoint methods and other advanced assimilation schemes will be considered.

There is a need for a workshop on data assimilation techniques in ecosystem models. Topics would include: (1) assembling a data set for intercomparison of models and assimilation techniques, (2) nested models and their use in coupled physical-biological-chemical systems, (3) assimilation techniques and their use in coupled physical-biological-chemical systems, and (4) cross disciplinary training of colleagues and students.

## 2.3 Observations, Experiments and Data Sets

A key facet of GLOBEC is the coupling of observations and modeling through an interdisciplinary data assimilative model. Such a construct will first be used for research purposes only, then for a combination of research and monitoring, and finally transitioned into an operational ecosystem monitoring system.

Data assimilation is a key element of such a system primarily because updating via assimilation controls phase error. Adjoint assimilation techniques can also facilitate the estimation of unknown parameters. Sufficient data can overcome shortcomings of model dynamics; conversely good models can reduce the need for data in the ecosystem monitoring system. A precise description of the variables to be measured and modeled needs to be developed. This includes (a) what should be measured with existing technology for useful input and verification of interdisciplinary models and (b) looking ahead in the near future, what measurements and variables would be desired? In both cases spatial and temporal resolution and accuracy requirements must be specified.

The design of a prototype ecosystem monitoring system ("test bed") was discussed. A goal was set for having instruments in the water within five years. A site with simple but interesting ecosystem dynamics should be chosen; the region should exhibit strong signals (e.g., an upwelling region). Other issues to consider in site choice are logistical convenience and the availability of satellite data. It is also of interest to elucidate the contrast between the coastal and deep oceans.

## 2.4 Interaction and Collaboration

A discussion was held concerning the role of NM-WG in facilitating cooperation in model development and the sharing and exchange of models and components of models. The idea of achieving true modularity, not simply within a given modeling group but community-wide, was emphasized. The concept of "community models" was debated and it was felt that it was desirable to do so but that further developments needed to be achieved first. A comprehensive review now by the community of coupled one-dimensional physical and biological models was considered timely.

At present the GLOBEC.INT NM-WG will communicate with other GLOBEC.INT working groups, regional GLOBEC programs, national GLOBEC programs, and related global change programs through individual NM-WG members serving as liaisons.

# 3. FINDINGS AND RECOMMENDATIONS

Three different working groups were formed at the meeting and charged with discussing the following issues:

*Observational and Modeling Variables*

Definition of quantities for assimilation and verification.

1. The desirable and feasible variables according to SOS report
2. The desired variables looking reasonably forward

*Test Beds*

An observational and modeling system for ecosystem dynamics research and monitoring.

1. Elements
2. Location
3. Duration

*Models and Methods*

Interdisciplinary data assimilation into nested multiscale models.

1. Model development
2. Dynamical and mathematical structure of biological, chemical and physical ecosystem models
3. Multiscales and nesting
4. Interdisciplinary data assimilation
5. Review and overview of status
6. Modularity and sharing
7. Intercomparisons

The full working group reports are included in Appendix A. Here we will summarize and then present the specific recommendations as recorded here and adopted by the entire NM-WG in the final plenary session.

It is an interesting time in ocean science now that for the first time there exist the scientific and technical bases for understanding biological-physical interactions, and the dynamics, variabilities, forced responses and sensitivities of regional and global ecosystems. The tasks of the NM-WG are feasible but lie at the research frontier of interdisciplinary modeling. A concerted program is required to develop and apply new models and methods, and to relate such models to observations and experiments with the optimal choice of biological state variables and adequate representation of biological rate parameters. Data assimilation is of paramount importance and its effective and efficient implementation requires the simultaneous and synergetic acquisition of biological, chemical and physical data from a mix of *in situ* and remote sensors deployed on a variety of platforms arranged in optimally designed arrays. The magnitude and importance of these modeling tasks are such that success can only be achieved through international cooperation and GLOBEC.INT NM-WG should provide the mechanisms for the required activities and interactions.

The design, development and deployment of a coupled numerical model/ observational system for ecosystem research and monitoring is necessary in order to achieve an understanding of, and to develop a predictive capability for, the global ecosystem. The system will be used for nowcasts, forecasts and realistic simulations. It should be generic, modular, portable and flexible with sophisticated and simple versions. The observational system must be multiplatform and multisensor. It will incorporate and integrate physical, biological and chemical measurements taken by ***in situ*** and remote sensors. The model component will be multiscale and interdisciplinary. The multiscale aspect will involve nesting of regions in larger scale domains with the possibility of two-way feedbacks and the coupling of coastal regions across the shelf-break to the open ocean. It will be capable of mesoscale resolution over large regions of critical biological/physical processes. Central to the system's functioning is data assimilation, i.e., the assimilation of matched physical, biological and chemical variables into the coupled interdisciplinary dynamical models. The field estimates obtained will be used for process studies, predicting the evolution of the ecosystems, and simulating the ecosystem dynamics and ecosystem change scenarios. Process studies will be carried out by balance of terms studies of physical and biological dynamical balances. Of particular importance are Observing System Simulation Experiments (OSSEs). Realistic simulations will be carried out and the four-dimensional multidisciplinary fields are then used as "true" oceanic data for the design and evaluation of observational systems, experiments, and sampling schemes. This method, first developed in meteorology, is now used in physical oceanography. It should be of particular importance to the design, development and utilization of the coupled ecosystem model/observational system. Several deployments should be carried out during the course of GLOBEC.INT, initially with a research orientation and finally with a monitoring orientation.

The specific recommendations of the NMWG are:

### 3.1 Variables:

1. It is recommended that careful attention should be paid to specification of important GLOBEC relevant variables in the manner in which they are observed and used in model contexts. The variables Table A1 of this report should be expanded and improved with respect to its presentation of core variables, usage, units and errors expected in their determination.

2. Phytoplankton measurements should include appropriate size fractionated analyses with sufficient resolution to differentiate between phytoplankton and other food sources of the target zooplankton in each GLOBEC effort. For example at a minimum measurements of biomass and primary production for cells < 5 µm to delineate microzooplankton and copepod food resources is crucial for North Pacific versus North Atlantic inter-comparisons. Coordination with JGOFS is desirable.

3. Maximal growth rates should be determined as a function of temperature under biochemically replete food conditions. These conditions should accurately reflect the nutritional sources for populations in the wild and be resolved to the extent that system shifts and adaptive variations are accounted for.

4. A working group should be established comprised of both observational and modeling investigators to develop methods for estimating both natural and predator-based mortality in target populations.

### 3.2 Test Beds: The Coupled Model/ Observational System

5. It is recommended that GLOBEC initiate the design of an integrated observational sampling and multidisciplinary assimilation system as a means of making significant progress in understanding the functioning of marine ecosystems. The aim should be to carry out at least two such exercises within the next 5-7 years.

6. It is recommended that, as a high priority, research should begin on designing and testing an ecosystem model that is structurally consistent with the biogeochemical and physical information that can be provided by remotely sensing instruments (deployed on both mooring and satellites).

7. It is recommended that, once potential study sites have been identified, Observational System Simulation Experiments be carried out to determine the appropriate mix of sampling platforms and the optimum utilization of such platforms to aid in the selection of sites and in array design.

### 3.3 Models and Methods:

8. The working group recommends that the international GLOBEC modeling program invest resources in the development of multiscale nested models that are capable of interdisciplinary data assimilation.

9. International GLOBEC should sponsor a series of annual workshops that are focused on various topics in interdisciplinary modeling. It is anticipated that these workshops will also provide a forum for training students and researchers in interdisciplinary modeling.

10. The modeling programs developed within international GLOBEC should maintain strong ties with groups doing data collection and data analysis. This interaction could be fostered through workshops that bring together observationalists and modelers. Furthermore, GLOBEC should develop a strong policy on data management and data sharing.

## 4. APPENDICES

### Appendix A. Working Group Reports

### A.1 Observational and Modeling Variables: Definition of Quantities for Assimilation and Verification (K. Denman (co-chair), D. Olson (co-chair), D. Cushing, and G. Fransz)

The variables working group was given the task to consider observational and modeling variables of interest to the GLOBEC ecosystem dynamics problem with requisite consideration of problems of population dynamics. The idea was to specify various variable suites necessary and useful to parameterize, initialize and verify models. Where possible there was to be an identification of the sensor suites or laboratory protocols which could provide inputs and which were feasible. This was to involve both current capabilities and possible developments during the course of GLOBEC.

The groups deliberations started with the variables involved in typical population models and their output. These are summarized in Table A1. These variables can be divided into parameters which occur in the model framework such as growth, death and reproductive rates and state variables such as biomass by component or environmental parameters. It is constructive to consider a generic model structure such as

$$\frac{DB_i}{Dt} = \frac{\partial B_i}{\partial t} + \vec{V}\,\nabla B_i + \frac{\partial s}{\partial t}\frac{\partial B_i}{\partial s} = u_{ij}B_iC_j - g_{ij}B_iD_j - a_iB_i.$$

Here $B_i$ is the particular biological variable of interest in the population, for example population density, biomass or mean individual weight, $C_j$ are resources, and $D_j$ are consumers of $B_i$. The total change in $B_i$ has been expanded to include the relative change in time, the effects of advection or active migration $\vec{V}$ and the influence of any variable, $s$ such as age, stage or genetic character which structures the population. The terms on the right in the equation are respectively the growth term, the predation/grazing or substrate related metabolic loss term, and a loss term which is not mediated by another variable. Of course, in general any of the functional forms on the right may also take logistic or other types of nonlinear form. As indicated in the table there are several possible choices for $B_i$ which will be found in any given model. The $u_{ij}$, $g_{ij}$ and $a_{ij}$ are proportionality constants, or more generally, functions of various variables and parameters. The summation convention is implied for $i,j$. In the minimal set $B_i$ will involve phytoplankton (P), zooplankton (Z) and nutrients (N) in some sort of currency such as nitrogen content. To adequately address the marine ecosystem this minimal set would typically be expanded to include different size fractions in both P and Z and more than one nutrient. In more sophisticated (complicated) models $B_i$ would be expanded to include both population mean individual mass and population density. The right-hand terms would then involve weight related mortality and population density dependent individual mass gain formulations.

The first question that arises in consideration of a system of equations such as that above is the decision of how many state variables are needed to treat the populations of interest in a particular ecosystem. The problem demands a complete specification of the structure of the environment from the organisms that inhabit it to the details of the mean circulation and eddy dynamics that control retention and dispersal within it. On the population level one might begin with a full analysis of all of the players in a given regime and an examination of the consequences of including or ignoring their contribution. Typically this could involve a series of measurements and test simulations to gain an appreciation of the problem prior to a choice of variables. In general, experience suggests that it is necessary and prudent to over sample initially. A similar analysis is required to ascertain the level of measurement effort needed in the physical representation of the environment.

**TABLE A1**. Required Data Types

| Variable: | Methods: | Resolution and Comments: |
|---|---|---|
| Phytoplankton:<br>Biomass: | Flourometric biomass; bio-optical prop.: | Satellite (SEAWIFS), *in situ* verif. underway, moored and profiles, at suffiecient resolution to calibrate and resolve forage resources. |
| Primary Production: | C-14 incubations: | Time course measurements both in *in situ* and on deck during underway work. Photo-sensitron P-I curves to the level needed to quantify vertical light behavior and in regions where vertical motion is expected to play an important role. |
| | Alternative methods: | Since the cost and time required for C14 incubations is prohibitive, alternative methods coming into use should be exploited. The proper level of effort should be carefully planned in an experiment design sense. |
| Zooplankton:<br>Biomass: | Traditional methods: | Network using appropriate mesh, space/time resolution to both ground truth acoustics and optical methods and provide biochemical material are crucial. Deployment should be carefully planned to insure fulfillment of the various requirements of this type of data. |
| | Acoustics: | Underway, moored and profiles: As an emergent technology, there will be various implementations during GLOBEC. At this time, one can suggest the following breakdown:<br>i) Single frequency/index measures for biomass; these require serious ground-truth and are primarily useful in concert with Doppler measurements of currents (i.e., as an auxilary measurement of opportunity)<br>ii) Multi-frequency instruments; minimaly 2 frequencies are needed to resolve even a crude stand let alone index of biomass. Various other arrays are currently available, if not yet routinely deployable.<br>iii) Multi-frequency/multiple beam technology. This technology provides the promise of imaging with available beam-forming technology from moorings; cost is, however, restrictive and interpretation becomes a harder issue. (See optical instruments, below.) |
| | Optical visualization: | This is again an important emerging technology with major promise in measuring biomass and community on line in a timely manner with attention to the issues of data flow and interpretation. |

| | | |
|---|---|---|
| Rates: | | |
| | Population growth: | These are probably the most crucial needs for models:<br>i) Growth, resolved as a function of temperature and food resource. The later need to reflect biochemically resonable forage scenarios.<br>ii) Grazing rates, again as a function of temperature and feeding history.<br>iii) Reproduction rates, as a function of age in stage and physiological condition.<br>iv) Mortality by stage and condition. As an ultimate "wish-list" this would include biochemical and some genetic information. (This demands overall knowledge of predators.) |
| | Dispersal: | These are really model checks, although they also provide data assimilation capabilities in some cases:<br>i) Lagrangian based studies with plausible relevant flow following characteristics to provide guidance to models.<br>ii) Field programs using the tools above in a pattern which allows estimates of population dispersal. |

Measurements of the state variables typically actually involve proxy measures such as chlorophyll fluorescence or acoustic biomass. It is assumed that model verification will either involve conversion to these proxy variables or a calibration of the estimates to actual population numbers. In most cases it is these conversions that represent most of the error in quantification. Division of the components in the ecosystem by size or even more definitively by species is often desired which places further demands on the observational and model system. In many cases the intercomparison of models and observations demands transformation of data in the form of both the observed variables and the model quantities. For example, fluorescence measurements might be size fractionated by using constants set by less frequent size dependent analyses and then converted to phytoplankton in terms of nitrogen content in two model pools. This requires two conversion factors, one from fluorescence to size fractionated chlorophyll and then chlorophyll to nitrogen. Similar conversions are required in almost every case except perhaps numerical counts. In almost any effort therefore there must be crucial efforts to specify the appropriate conversion factors and their uncertainty.

Beyond the specification of state variables there is the question of the parameters on the right side of the equations. Specification of these involves an appropriate choice of parameterization and then delineation of the parameters in the equation and their dependence on environmental variables. The group felt that a major component of any GLOBEC effort must involve a careful treatment of growth, death and reproduction in the various populations of interest. In particular, maximal growth rates for both phytoplankton and zooplankton as a function of environmental temperature and substrate availability are a high priority. In particular the dependence of zooplankton growth rate on both temperature and food is required. Where possible this should be biochemically replete with respect to the natural feeding habitat of the animals. Attention should be paid to the internal storage of resources such as nutrients in phytoplankton and lipids in copepods. Most of these involve dedicated laboratory studies with verification in the field as feasible. The problems with parameters becomes even harder in the case of mortality.

It is wise to consider population loss in terms of both a natural mortality term, i.e., death of individuals due to age or disease, and grazing or predation losses. The problem of even how to parameterize the death term in zooplankton is a matter of considerable debate and its resolution will require careful attention both in terms of data collection and modeling. If possible the minimum death rate rate for zooplankton and the senescence rate for phytoplankton should be quantified. The population dependent losses present several observational challenges. Cohort methods may be applied but place considerable demands on sampling frequency and typically demand strong assumptions on the homogeneity of the population in space and time. In the case with two sources of mortality it is also advantageous to apply a virtual population analysis. The basic constraints on these with respect to data are available in the literature. Finally, death rate should be specified with respect to other parameters such as temperature of population structure.

There are various reproductive and behavior related parameters which are required for a full simulation of populations. These include fecundity and its dependence of physiological state and food, environmental parameters involved in migrations and the limits to response to controlling taxis, the factors involved with incystation in phytoplankton and microzooplankton and diapause in macrozooplanktors. Again, in most cases there is a need for serious laboratory efforts in most of these cases. Eventually means of addressing these quantities in the field may become available.

### A.1.1 Recommendations

(V.1) Careful attention should be paid to specification of important GLOBEC relevant variables in the manner in which they are observed and used in model contexts. The variables of Table A1 of this report should be expanded and improved with respect to its presentation of core variables, usage, units and errors expected in their determination.

(V.2) Phytoplankton measurements should include appropriate size fractionated analyses with sufficient resolution to differentiate between the food sources of the target zooplankton in each GLOBEC effort. For example at a minimum measurements of biomass and primary production for cells < 5 µm to delineate microzooplankton and copepod food resources is crucial for North Pacific versus North Atlantic intercomparisons. Coordination with JGOFS is desirable.

(V.3) Maximal growth rates should be determined as a function of temperature under biochemically replete food conditions. These conditions should accurately reflect the nutritional sources for populations in the wild and be resolved to the extent that system shifts and adaptive variations are accounted for.

(V.4) A working group should be established comprised of both observational and modeling investigators to develop methods for estimating both natural and predator based mortality in target populations.

## A.2 Test Bed: An Observational and Modeling System for Ecosystem Research and Monitoring (M. Fasham (chair), T. Dickey, M. Kishi, C. Moloney, and P. Nival)

### A.2.1 Elements

It was the considered view of the working group that future progress in understanding the functioning of marine ecosystems will only be possible by implementing integrated sampling systems and assimilating the observations obtained therefrom into multi- and interdisciplinary simulation schemes and models. Such a coupled numerical model/observational system could provide both real-time nowcasting and forecasting during cruises and also represents the only feasible method of coping with the problems of adequately sampling the oceanic system. It is critically necessary for research and for the development of monitoring and predictive capabilities in the global change context. The basic building blocks of such a system, which could sample ecosystem properties over time scales of months to years and space scales up to 1000 km, are described below. The details of the system and sampling design which would be needed for a given application, such as the mooring spacing, the vertical spacing of instruments on a mooring, the spacing and deployment frequency of drifting buoys and ship survey transects, must be determined using an Observational System Simulation Experiments (OSSEs). It is essential that a high priority should be given to obtaining funding for an OSSE exercise to design the first proposed GLOBEC assimilation experiment.

### A.2.1.1 Experimental Design

The experimental design distinguishes the far-field (space scales from ~ 100—1000 km) from the near-field (space scales O (internal radius of deformation, or 10—100 km). The far-field will be sampled using, e.g., ship surveys, an array of moorings around the 1000 km box, drifting buoys, and remote sensing satellites, aircraft and moorings. The near-field will be sampled from additional sensors such as profiling systems.

### A.2.1.2 Moorings

The instruments to be placed on the moorings should be chosen using the following criteria; they should attempt as far as is possible to cover the biological size spectrum of interest to GLOBEC, distinguish where possible between different functional types (e.g., heterotrophs versus autotrophs), delineate the physical fields required for the physical models, and sample with sufficient temporal resolution for the assimilation programs. The GLOBEC.INT SOS Working Group report describes in more detail the instruments that are available, or will become available within the next 2—3 years, but a possible set of instruments for the moorings would be ADCP, VACM, bio-optical package (light meters, transmissometer, fluorometer, particle counter), nutrient sensors, multi-frequency acoustics, temperature and conductivity sensors, and video cameras. The exact choice of sensors on the near- and far-field mooring arrays would be determined by the OSSE exercise. Some fixed moorings using continually profiling instruments (sampling temperature, conductivity, PAR, transmittance, and high-frequency acoustics, between 0—500m) could also be deployed. Moorings would have a surface buoy capability with a meteorological and satellite telemetering package.

### A.2.1.3 Drifting Buoys

Instrumented drifting buoys would provide quasi-Lagrangian information at smaller space scales than the other sampling platforms but would also roam throughout the large domain. Such information would be used as part of the assimilation but could also be used to estimate the spatial spectrum of the biological fields for parameterizing the smaller scale physical and ecosystem processes. Automatic profiling instruments could also be connected to drifting buoys. The drifters would be designed to have an operational duration of at least several months.

### A.2.1.4 Ships

Ships can be divided into two classes, mobile and static. The mobile ships will be used to measure the near- and far-field spatial patterns of both physical and biological variables, both for initializing the assimilation model and updating it at regular intervals. These ships would need to be equipped with a towed undulator measuring temperature, salinity, chlorophyll fluorescence, PAR, nitrate and other nutrient concentrations, particle size structure, and possibly high frequency acoustics. Ideally, the undulator would be capable of sampling down to 500—600 m. The mobile ships would also measure surface fluorescence, nutrients, and other biogeochemical variables from the pumped surface water supply, and be provided with an ADCP and other acoustic samplers.

The static ships would normally sample within the near-field mooring array and would make biological and physical measurements that cannot be made from moorings (e.g., biological rate measurements, physical microstructure, bacterial sampling, zooplankton net samples) and also take measurements for calibrating the various instruments on the moorings. New experimental techniques that require laboratory-based facilities such as genetic fluorescent markers and flow cytometry could also be carried out on these ships.

The development of these mooring arrays and coupled ecosystem and physical assimilation models will, in the future, enable ship usage to be minimized. However, in the early stages of the program it would seem advisable to have sufficiently more ships to allow for the necessary oversampling of the fields to establish minimum data requirements and to test the efficiency of the assimilation programs with varying spatio-temporal coverage of observations.

### A.2.1.5 Remote Sensing

Satellites will be used to provide information on the far-field for the assimilation program and it would be desirable if this information could be provided to the ships in near real-time. The fields that are required are altimetry, surface temperature, cloud cover, ocean color, and scatterometer (surface winds). Based on the available information on future plans for launching satellites, it was considered that most of the required observations should be available during the planned period of the GLOBEC program.

As well as remote sensing from satellites, aircraft could be used to drop AXBTs and measure the surface chlorophyll concentration giving further information on both near- and far-fields for assimilation.

### A.2.1.6 Models

The physical component of the assimilation model will require a horizontal resolution of 3-5 km within the near-field box but could have a coarser resolution outside this box, assuming that suitable spatially-nested algorithms can be developed. Due to the small-scales of some biological patchiness it may be necessary to have a finer horizontal grid for the biological model, in which case interpolating the physical fields should be carried out by modern efficient methods such as empirical orthogonal functions.

The structure of the ecosystem model must, as far as possible, be isomorphic with the biological fields being sampled by the moorings, ships, and satellites. This will require some initial analysis to determine what size and functional biological groups are measured by the array of acoustic and optical instruments, followed by the development of suitable models. This work should be initiated as soon as possible to ensure the assimilation package is available and has been tested by the time the program gets underway. These issues are addressed by the Variables and Models Working Groups (Sections A.1 and A.3).

### A.2.2 Location of Test Beds

A number of possible locations for the implementation of the initial test beds were discussed. The criteria that may assist in making such decisions include:

1. Degree of cloud cover. For comprehensive satellite coverage for data assimilation purposes, it is necessary to choose an area with a reasonable frequency of cloud-free days (generally require >50% cloud free). However, as a number of interesting study sites would not meet this criteria, the general system should be designed so that extensive satellite coverage is not necessarily required.
2. Accessibility. It may be necessary to visit the test site for "maintenance" purposes, in addition to routine scientific cruises.
3. Degree of prior knowledge. The test bed location should be in an area that has been fairly well studied.
4. Minimum biological signal. The minimum magnitude of the biological signals (e.g., biomass) that can be measured by the mooring instruments may rule out some initial study sites in highly oligotrophic areas.
5. Physical/biological event. It may be desirable to choose a site at which a "predictable" biological event occurs, e.g., spring bloom or upwelling event.
6. Simplicity of ecosystem. A reasonably simple ecosystem with few dominant species may be preferable to an ecosystem with a diverse community with no clear dominants.
7. Interesting scientific issue. The area chosen should be capable of addressing a specific scientific issue regarding biological/physical interactions, of interest to the scientific community and relevant to the goals of GLOBEC.
8. Retentive systems. It may be necessary to choose an area with a relatively closed system, to minimize or limit imports and exports through advection.
9. Weather. Local weather conditions should be conducive to ship-board work.
10. Sizes, types and durations of physical features. Physical processes of interest should be represented adequately within the study area and period.

Suggested areas (these are not listed in any order of preference)

| **Cloudy** | **Relatively Cloud Free** |
|---|---|
| North Sea | Mediterranean (Gulf of Lion/ Villefranche) |
| Georges | Catalan Sea Bank |
| MLML (60°N, 20°W) | Benguela/Agulhas Bank region |
| Biotrans (47°N, 20°W) | JGOFS BATS site |
| OWS "P" | JGOFS HOTS site |
| Baltic Sea | California/Oregon |
| Celtic Sea | Peru upwelling |
| Kuroshio | |

### A.2.3 Timing and Duration of Program

Bearing in mind the development time for hardware and software, we envisage that the first full-scale test of such a system should take place 4-6 years from the present. We envisage at least two separate exercises, the first being in a region of high biomass in order to give the best signal-to-noise ratio for the mooring instruments, the second being in a more oligotrophic, low biomass area with the possibility of extensive satellite coverage. Each exercise would aim to deploy the moorings for a period of about a year but would contain a number of shorter periods when more concentrated sampling with ships and aircraft would be carried out.

### A.2.4 Recommendations

(T.1) It is recommended that GLOBEC initiates the design of an integrated observational sampling and multidisciplinary assimilation system as a means of making significant progress in understanding the functioning of marine ecosystems. The aim should be to carry out at least two such exercises within the next 5-7 years.

(T.2) It is recommended that, as a high priority, research should begin on designing and testing an ecosystem model that is structurally consistent with the biogeochemical and physical information that can be provided by remotely sensing instruments (deployed on both mooring and satellites).

(T.3) It is recommended that, once potential study sites have been identified, Observational System Simulation Experiments be carried out to determine the appropriate mix of sampling platforms and the optimum utilization of such platforms to aid in the selection of sites and in array design.

## A.3 Models and Methods: Interdisciplinary Data Assimilation into Nested Multiscale Models (E. Hofmann (chair), T. Komatsu, J. Nihoul, G. Radach)

Note: In this report, nested models refer to fine resolution models that are embedded in coarser resolution models. Couplings between these models can occur in any number of dimensions and include a range of space and time scales. Couplings may be from fine to coarse scale or vice-versa or both.

### A.3.1 Dynamical and Mathematical Structure

Addressing the objectives of GLOBEC will require a variety of models and modeling approaches. Therefore, any modeling program developed as part of an international GLOBEC effort should be broad enough to encourage the development and implementation of models that consider processes that operate at short space and time scales (e.g., the scale of the individual) as well as processes that occur on longer scales, e.g., mesoscale, regional scale basin or climate scales. The modeling program envisioned as a component of GLOBEC will of necessity require new approaches. In this section, we discuss some of the conceptual and technical issues that will need to be considered in developing models for GLOBEC and make some recommendations as to how these issues may be addressed.

1. Nested Models. It is likely that the models developed as part of GLOBEC will initially be focused on specific regions. However, these models will require information about processes that operate at longer space and time scales that occur outside the region of interest. One approach is to develop fine scale models that are embedded in coarser resolution models, with coupling between the models that allows information to be transferred about the longer scale processes. This is already being done with atmospheric and ocean circulation models. For interdisciplinary studies this would require that both the coarse and fine scale models include biological and chemical dynamics.

2. Formulations/Parameterizations of Biological Processes. Formulations used for biological processes typically are based upon empirical information. However, some accepted formulations, such as Michaelis-Menton kinetics, are routinely used in biological models. These need to be tested in a variety of models that consider a range of length and time scales to determine the effect (if any) the specific formulation has on the model solutions. A variety of formulations need to be considered for similar processes (e.g., linear versus quadratic formulations for expressing predation losses) to determine the effect on model solutions. Also, consideration needs to be give to how formulations that are used in fine scale models can be transferred to coarser scale models so that relevant dynamics are preserved.

3. Individual and Population Models. Most measurements are made at the level of the individual and these are useful for describing processes in individual based models. However, most physical-biological models are developed to consider processes that affect populations. Hence, techniques are needed that will allow information developed for an individual organism to be transferred to the population scale.

4. Consistency Between Data and Models. One application for modeling is to provide a structure for data acquisition. This must be realized by developing conceptual models around which field programs or sampling

systems are designed. This would ensure that the type and resolution (space and time scales) of measurements would be consistent with what is needed for modeling.

5. Boundary Conditions. This topic includes the need for initial distributions for model variables as well as the need for providing time or space dependent boundary conditions for model operation. For initialization, it may be possible to extract some useful input from historical data bases to produce climatological distributions for model initialization. However, for many biological variables (e.g., certain life history stages of a copepod) there is frequently insufficient historical data to obtain a distribution. Efforts should be made to identify existing data bases for interdisciplinary modeling studies and to identify where these data bases may be lacking. Additionally, remotely sensed distributions (e.g., ocean color) can provide quasisynoptic initial distributions as well as time and space varying boundary conditions for models. Moored instrumentation and the proposed developments in this area (see Test Bed Section A.2 and GLOBEC Report No.3) may also provide data of the type needed to specify time and space dependent boundary conditions for models.

6. Structured Population Models. Moving from a simplified or bulk ecosystem approach (e.g., single phytoplankton or zooplankton component) to one in which various trophic levels are size or stage structured provides better representation of biological and population processes, and the ability to isolate specific biological or physiological features (e.g., stage-dependent migration behavior). Overall this should give a better understanding of the processes that structure various trophic levels and marine ecosystems in general. However, such an approach requires increased knowledge of specific organisms, and more measurements of individual processes and rates.

### A.3.2 Assimilation of Data into Interdisciplinary Models

Data assimilation provides a mechanism for adjusting model parameters relative to a known distribution, updating the model at various intervals and improving the accuracy of simulated distributions. Data assimilation has been used with meteorology and ocean circulation modeling studies and is now starting to be used with biological models. This section discusses some issues associated with assimilation of biological data. Data assimilation can compensate for model deficiencies, maintain synoptic phase information in the presence of loss of predictability, provide dynamical space time interpolation of sparse data, and estimate poorly known parameters such as boundary conditions, eddy viscosities or biological rates.

1. Ecosystem Updating. One consideration of assimilation of data into ecosystem models is that if one component of the model ecosystem is updated, then all other components of

the ecosystem must be consistently adjusted. This requires the development of techniques and algorithms for assimilation so that model domains can efficiently constrain the biology when only one or a few components of the ecosystem are updated with data.

2. Parameter Estimation. Some data assimilation methods, such as adjoint methods, allow recovery of estimates of parameters through the assimilation of data. These approaches have the potential of providing considerable insight into the rates and processes that are responsible for observed biological distributions.

3. Updating of Models. A considerable literature exists on the application of objective analysis and Kalman filtering techniques as applied to data assimilation. These approaches hold considerable potential for assimilation of biological distributions, such as ocean color measurements or acoustic measurements, into ecosystem models. This is an area that should be explored.

4. Sampling and Data Needs. The availability of observations for data assimilation, as well as for boundary conditions, deriving parameterizations and model verification, is crucial for GLOBEC as a whole. Strong ties need to be made between the modeling and the sampling and observation components of GLOBEC to ensure that data adequate for models is obtained. Models can also provide a framework for data analysis and data consistency testing.

### A.3.3 Recommendations

(M.1) It is recommended that the international GLOBEC modeling program invest resources in the development of multiscale nested models that are capable of interdisciplinary data assimilation. This is an area where GLOBEC can make a fundamental contribution and advance in interdisciplinary modeling.

(M.2) International GLOBEC should sponsor a series of annual workshops that are focused on various topics in interdisciplinary modeling. It is anticipated that these workshops will also provide a forum for training students and researchers in interdisciplinary modeling. The final product of these workshops would be a book. Some suggested topics for the workshops are:

-a review of the state-of-the-art in interdisciplinary modeling, with directions for future research
-statistical and analytical approaches for transferring information from individual to population scales in biological models
-techniques and approaches for assimilation of biological data into biological models
-approaches for formulations for biological processes
-coupled mixed layer and biological models, and intercomparisons of these models

(M.3) The modeling programs developed within international GLOBEC should maintain strong ties with groups doing data collection and data analysis. This interaction could be fostered through workshops that bring together observationalists and modelers. Furthermore, GLOBEC should develop a strong policy on data management and data sharing.

## Appendix B. Introductory Presentations

### B.1 1-D Mixed Layer Models and Biology

Kenneth K. Denman

#### B.1.1 Representation of Vertical Transport or Diffusion

In most mixed layer models the vertical turbulent diffusion or mixing decreases to zero below the current bottom of the 'mixed layer.' Physically, zero vertical mixing is unrealistic because there exists evidence of sporadic mixing events in the pycnocline resulting from the interaction of internal waves with vertical shear in horizontal currents causing internal wave breaking. Moreover, biologically there appears to be sufficient primary production throughout the summer to require some upward vertical fluxes of nutrients through the pycnocline. Many models now allow a 'background' turbulent diffusion that is constant with depth and of order $10^{-5}$ $m^2s^{-1}$. This is an arbitrary 'fix' to a process that the models may be most sensitive to and clearly needs to be addressed in the near future.

#### B.1.2 Modeling Trajectories of Individual Organisms

Modeling of the transport of individual organisms by the fluid flow requires 'Lagrangian' flow calculations. Most one-dimensional models of the mixed layer do not include explicit velocities in three dimensions. Thus calculation of the Lagrangian trajectories of individual organisms usually involves an arbitrary construct to estimate individual vertical movements due to the flow field. An early attempt was that of Woods and Onken (1982), who cycled individual plankton over the whole thickness of the mixed layer with a sinusoid of period of about 30 min, to represent the time scale of the large energy-containing eddies. They superimposed on the sinusoid every time step (3 minutes) a random jump to represent small-scale turbulent mixing. Yamazaki and Kamykowski (1991) tried a more realistic simulation by modeling the vertical excursions as random Brownian motion where the step size was weakly dependent on the stratification. Thus the steps were larger in weaker stratification. The results were encouraging from a biological viewpoint, but such Lagrangian calculations with a vertically varying random step size imply unmixing of other scalars or the concentrating of water molecules in stratified layers, both physically unrealistic. (See comments in press in Deep-Sea Res. by Holloway, and by Yamazaki and Kamykowski). Such a representation of the mixing as a small-scale diffusive process does not capture the vertical transports of organisms by the organized large energy-containing eddies now being observed in the upper ocean. We require new representations of the Lagrangian trajectories of individual organisms that are consistent with known physical processes.

## B.1.3 Report of a Modeling Workshop at Woods Hole, MA in June 1993

In June 1993 a workshop sponsored by the US Office of Naval Research was held at Woods Hole under the leadership of Cabell Davis and John Steele. The purpose of the workshop was to attempt to couple several mixed layer models with 'simple' biological models. Several linked UNIX workstations were dedicated to the workshop as well as a Macintosh and a 486-PC. The workshop evolved into 3 groups:

a) a group developing a food-web model including a microbial loop
b) a group developing a food-web including multiple stages of cohorts of zooplankton
c) a group coupling several mixed layer models with simple Nutrient-Phytoplankton-Zooplankton-Detritus (N-P-Z-D) models.

The first two groups made considerable progress during the workshop but there was inadequate time to attempt to couple these models with mixed layer models. Here, I report only on the progress of the third group, which was due primarily to the efforts of Glenn Flierl of the Massachusetts Institute of Technology. Prior to the workshop, he had taken versions of the Price, Weller and Pinkel (1986) and Mellor and Durbin (1975), employing a Mellor-Yamada Level 2 turbulent closure, mixed layer models (PWP and MY), and had removed all boundary heat exchanges and wind stress to common program modules. He had developed a simple convective adjustment model (CONV) that had a constant mixed layer depth or a depth equal to the convective adjustment depth for surface cooling, whichever was deeper, and a simple N-P-Z biological module to be used with each of the mixed layer models. Peter Franks of Scripps Institution of Oceanography also contributed to the work described below. Several other people worked on versions of mixed layer models with similar biological models (one including detritus and recycling), and summaries of all the projects will be included in the report of the workshop.

All models were run with annual cycles of solar heating and back radiation tuned to give no net heat exchange over the whole year. PWP and MY were run with a constant wind stress, and CONV was run with no wind mixing. The first two days were spent comparing the mixed layer models. PWP and CONV compared closely, as indicated by comparing the annual cycle of surface layer temperature and occasional vertical temperature profiles. MY did not conserve heat due to a numerical problem which was repaired. Also MY has a built-in background diffusion of 1.34 x $10^{-5}$ $m^2s^{-1}$ in addition to the vertical profile of turbulent diffusion that is calculated by the model each time step. We found that the background diffusion was too efficient at transferring heat downwards (and presumably nutrients upward) so turned it off for the runs including the biological module. It appeared that MY took at least ten times as long as PWP to run an annual cycle.

A simple N-P-Z biological module was formulated to be coupled with the mixed layer models. It had Michaelis-Menten nutrient uptake and light response functions and an Ivlev grazing function without a threshold prey concentration. The equations are those below:

$$\frac{dP}{dt} = \mathrm{uptake} - \mathrm{grazing} - pm * P$$

$$\frac{dZ}{dt} = ga * \mathrm{grazing} - zm * Z2$$

$$\frac{dN}{dt} = -\mathrm{uptake} + pm * P + (1 - ga) * \mathrm{grazing} + zm * Z2$$

$$\mathrm{grazing} = rm * P * Z * (1 - \exp(- * * P))$$

$$\mathrm{uptake} = vm/(ks + N)/(I + ib) * I * P * N$$

We first coupled this model to the convective adjustment mixed layer model CONV and used parameter values suggested by various meeting participants. We changed parameters fairly freely for a while obtaining Lotka-Volterra like limit cycles of order days to weeks that propagated downwards through the water column as the nutrients were used up in the surface layers. Eventually, we found a set of parameter values that gave annual cycles of N, P, and Z characteristic of a high nutrient, low chlorophyll region like the subarctic Pacific where the heating and mixing impose a clear annual cycle on the planktonic ecosystem, but no spring bloom in phytoplankton biomass develops and near-surface nutrients are not exhausted. The top panel of Figure B.1.1 shows a two-year run starting at day 100 of the first year: in the second year (after model spinup) there is only a hint of a spring bloom. The bottom panel shows the result of increasing ib by a factor of 3, that is increasing by a factor of 3 the amount of light required for a rate of phytoplankton production half the maximum or saturation value. In this case a spring bloom in phytoplankton develops after the spring density stratification has been established. In the top panel increased growth at low light allowed P and Z to maintain relatively high biomass levels over the previous winter period, so that when primary production increased in the spring of year 2, there was sufficient zooplankton to graze down the phytoplankton. In the lower panel, lower winter phytoplankton abundances resulted in lower zooplankton abundances such that the zooplankton could not graze down the spring increase in primary production and a short bloom occurred. In neither case was the nutrient depleted during the summer months.

Figure B.1.2 shows the same biological model runs with the biological module coupled with the Mellor-Yamada (MY) model. Although the MY mixed layer depth had not achieved a repeatable annual cycle, the biological cycles were almost identical for the two mixed layer models, suggesting that the annual heating cycle imposes a strong control over the annual cycle in the biological variables. We do not know if this is a general result: after all, this simple biological model has 8 adjustable parameters so we have explored exactly 2 points in an 8-dimensional parameter space (see Table B.1.1). As the MY model was run without background diffusion, we have not addressed what is probably the major sensitivity of such systems in central oceanic gyres to mechanisms of supplying nutrients to the euphotic zone. We intentionally left coupling with the PWP mixed layer model until the end because a number of participants had previous experience with that model. However, Glenn Flierl plans to make runs with the biological model coupled with a PWP model for inclusion in the report of the workshop.

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**Yamazaki, H., and D. Kamykowski (1991)** "The vertical trajectories of motile phytoplankton in a wind-mixed water column" Deep-Sea Res. 38: 219—241.

**Table B.1.1** Values of parameters used in the 'no bloom' and 'bloom' runs shown in the top and bottom panels of Figs. B.1.1 and B.1.2. Initial values were N=1.95, P=2.7, and Z=0.35.

| **Parameter** | **No Bloom** | **Bloom** |
|---|---|---|
| vm | 2.0 | 2.0 |
| ks | 0.1 | 0.1 |
| ib | 0.5 | 1.5 |
| pm | 0.05 | 0.05 |
| rm | 0.35 | 0.35 |
| * | 1.0 | 1.0 |
| ga | 0.7 | 0.7 |
| zm | 0.2 | 0.2 |

**Figure B.1.1.** A two-year run of the convective adjustment mixed layer model CONV forced by an annual heating and cooling cycle. The biological model used the parameter values given in Table B.1.1 for the 'No bloom' (upper panel) and 'Bloom' (lower panel) cases. MLD - mixed layer depth, N — nitrate, P - phytoplankton concentration, and Z - zooplankton concentration.

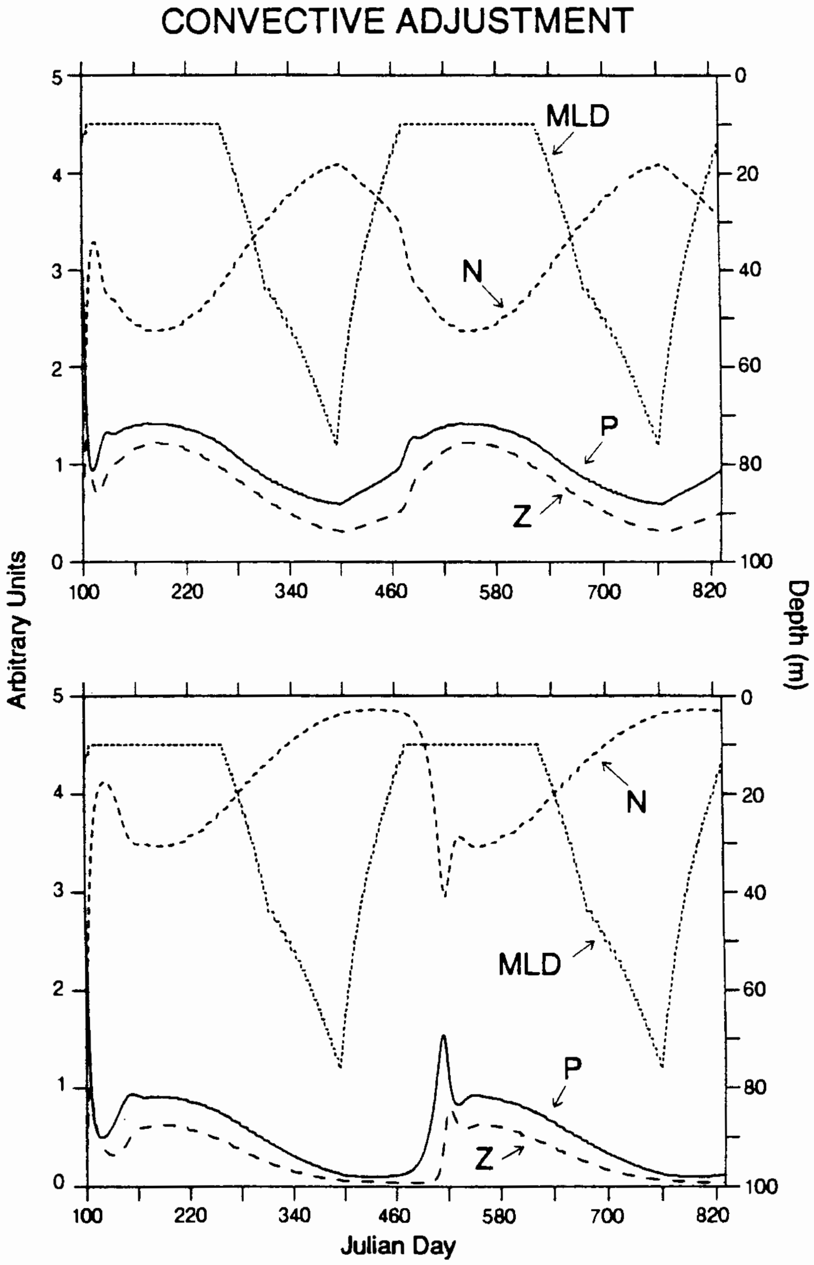
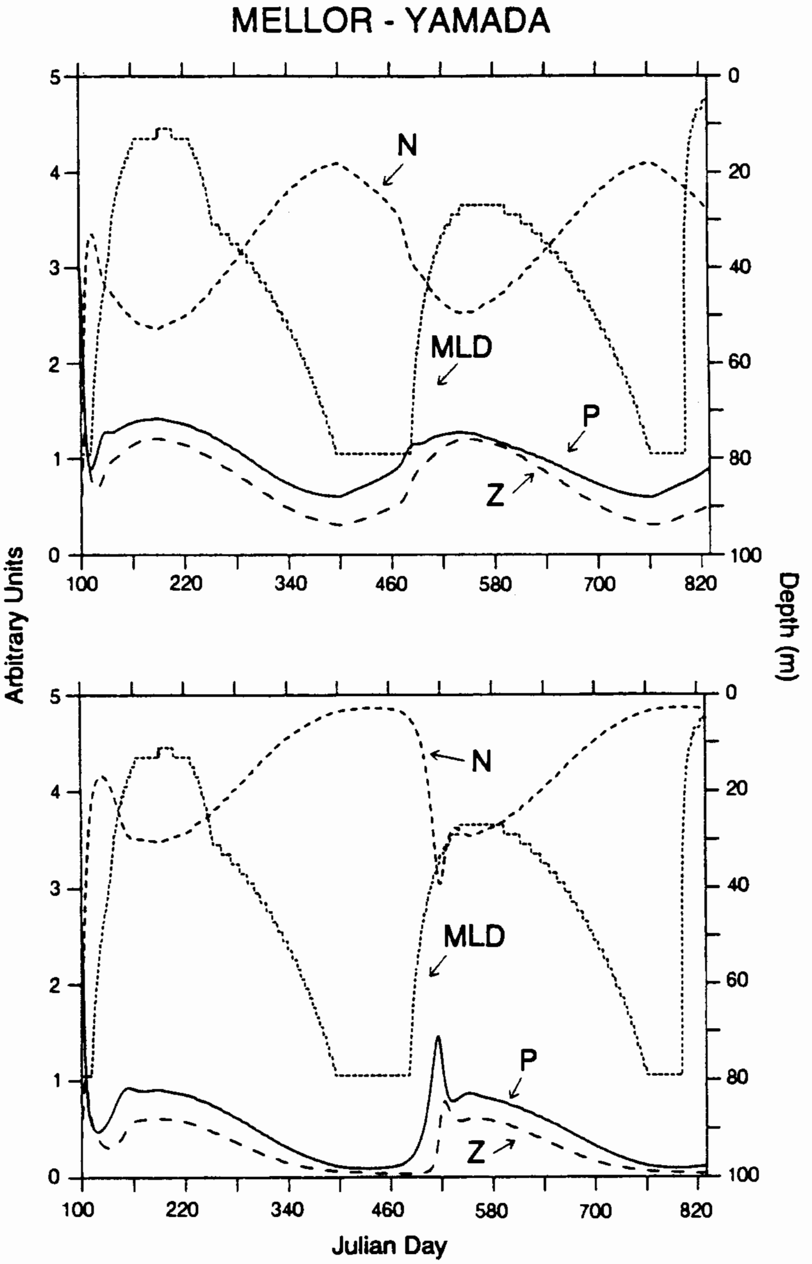


**Figure B.1.2.** A two-year run of the Mellor-Yamada mixed layer model MY with the same heating and cooling cycle as Fig.B.1.1 but with a constant wind. The biological model was identical to that in Fig.B.1.1.



## B.2 Modeling Seasonal Cycles of Production in the North Pacific and North Atlantic Oceans

Michael J.R. Fasham

Differences between the seasonal cycles of phytoplankton in the subarctic Pacific and Atlantic Oceans have been the subject of much speculation in recent years (Parsons and Lalli, 1988). In the North Atlantic observations at Ocean Weather Station "India" (59N 19W) have shown that winter chlorophyll concentrations were usually 0.1 mg $m^{-3}$ and there was a pronounced spring bloom with peak values in excess of 1 mg $m^{-3}$. In contrast the North Pacific the seasonal cycle appears to be far less pronounced with an average seasonal change in chlorophyll concentration at Ocean Weather Station "Papa" (50N 145W) of only 0.2 mg $m^{-3}$. This difference in the phytoplankton cycle is reflected in the nitrate observations; at "India" the summer nitrate concentrations are between 1-2 mMol $m^{-3}$ whereas at "Papa" summer concentrations rarely fall below 7 mMol $m^{-3}$.

There have been a number of explanations for these large differences in the production cycle but there are 5 main theories:

1. Differences in Physical Structure

The differences in meteorological conditions and basin structure mean that there is no Atlantic type deep mixing in the North Pacific resulting in a permanent halocline at ca. 150 m. Evans and Parslow (1985) suggested that this meant that a significantly higher winter primary production was possible in the North Pacific compared to the Atlantic with the result that over-wintering zooplankton biomass was sufficiently high at the time of the spring stratification for the total grazing to match the primary production.

2. Difference in the Algal Growth Rates

Martin and Fitzwater (1988) suggested that algal growth in the subarctic Pacific is limited by iron not nitrogen. In contrast, iron does not seem to be limiting in the subarctic North Atlantic.

3. Differences in the Zooplankton Grazing Rates

Frost (1987) has shown from model studies that it is possible to reproduce the Pacific seasonal cycle by assuming a strong role for protozoan grazers with grazing rates that match algal growth rates (ca. 2 $d^{-1}$). The major question that must then be asked is why are protozoan grazers more important in the North Pacific compared with the North Atlantic? Another possibility is that the lack of iron favors smaller phytoplankton and thereby a greater role for protozoan grazers (Miller et al., 1991).

4. Differences in Zooplankton Mortality Rates

Steele and Henderson (1992) studied a simple P-Z-N model and showed that if a quadratic zooplankton mortality function was assumed (in contrast to a linear function) then it was possible to generate either Pacific or Atlantic seasonal cycles by varying the constant of the mortality function.

## 5. Differences in Zooplankton Life Histories

One of the early explanations for the difference was that the ontogenetic migration of Pacific Neocalanus populations was such that it enabled them to exploit the spring increase is algal growth rate as soon as it occurred (Frost, 1987). However, the work of the SUPER program showed that the biomass of Calanus was insufficient to account for the estimated grazing of phytoplankton in the spring (Miller et al., 1991).

Many of these hypotheses should, and are, being investigated by observational programs. However, it is also interesting that at least three of them have been tested, or even, first suggested by modeling studies. However, each of these studies (Evans and Parslow, 1985; Frost, 1987; Steele and Henderson, 1992) used a different ecosystem model and different physical forcing. In order to make further progress it is necessary to test the alternative hypotheses using the same ecosystem model and the same forcing. I am presently carrying out such a study using the simple mixed layer model of Evans and Parslow (1985) and a three-compartment ecosystem model based on that of Steele and Henderson (1992). The work is still in progress but the conclusions obtained so far are that a transition from the North Atlantic to North Pacific cycles can be achieved by, either decreasing the mortality rate of zooplankton, or increasing the ratio of the zooplankton grazing rate to phytoplankton growth rate. However, it has not so far been possible to choose an ecosystem parameter set such that the transition between the two types of seasonal cycle can be achieved by simple changing the physical forcing from the Pacific situation to the Atlantic. It is clear that the Pacific-Atlantic differences in the production cycle provide a critical test for any ecosystem model that is intended for use in a global simulation of the marine ecosystem.

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## B.3 Identification of Functional Units for Zooplankton and its Food

H. George Fransz

In most mesoscale and large-scale models the zooplankton is represented by a single state variable, and it ingests only phytoplankton. Such a simple presentation of the role of zooplankton neglects the very nature of marine plankton systems, which in general must function at low levels of resources such as nutrients and light. Under such conditions the system is dominated by small algae (nano- and picophytoplankton), which are consumed by microzooplankton such as ciliates and heterotrophic flagellates. Then the microzooplankton is the main food of mesozooplankton such as copepods. The controlling resource tends to be retained in the system by rapid recycling of nutrients and/or low sinking rates. This retention system is the basic system virtually everywhere in the sea. Many mesozooplankton species are adapted to utilize the microheterotrophs at least in periods of low density of the larger algae. In more eutrophic areas and time periods micro- and mesophytoplankton can build stocks on top of that, and will then form the main food of copepods.

This structure may explain why in "low resource" areas such as the Southern Ocean small-sized copepod species *(Oithona similis)* dominate the zooplankton biomass and why the copepods here develop copepodite stages and population biomass during the Antarctic fall and winter when algae have a low abundance. For realistic models it seems necessary to distinguish different size classes of algae, microzooplankton and mesozooplankton as functional groups with different food requirements and seasonal dynamics.

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## B.4 Numerical Methods and Data Assimilation

Eileen Hofmann

This presentation focuses on some issues that arise when constructing numerical models for physical and biological interactions in marine systems. The emphasis is placed on aspects of models that are important when considering secondary production and marine animal population variability.

### B.4.1 Scaling

The largest and smallest space scales that numerical models of circulation and biological processes can resolve are determined by the model domain and grid size, respectively. Processes that operate at scales larger than the model domain are input through the boundary conditions. Those smaller than the model grid are handled through parameterizations that represent subgrid-scale processes (e.g., turbulent diffusion). The range of time scales that can be resolved in numerical models is usually determined by the time scale of the process of interest and the time interval used for the numerical integration.

Circulation and biological processes have associated with them certain inherent space and time scales. For example, the scales of spatial structures observed for marine plankton distributions can be represented in terms of balances between diffusion, growth (the Kierstead-Slobodkin length scale) and grazing processes. Other fundamental scales, such as mixed layer or euphotic zone depths, are important in regulating the spatial distribution of plankton populations. Also, inherent time scales such as population doubling times, diurnal variations in light or seasonal changes in nutrient inputs impart spatial structures to marine ecosystems that may need to be resolved in models. Circulation processes tend to be influenced by length scales, such as the internal Rossby radius of deformation and the geometry of a basin or shelf region. The dominant physical time scales are usually determined by processes, such as tidal forcing, episodic wind and storm mixing of the upper ocean and seasonal changes in large-scale wind systems, for example.

Constructing circulation or biological models that can resolve specific ranges of space and time scales is usually not difficult. The difficulty comes when attempting to combine circulation and biological processes in a single model. Often the resolution requirements for each are different and can be contradictory. For example, large-scale circulation models do not usually include mixed layer dynamics which are quite important for structuring upper water column biological systems.

### B.4.2 Data Assimilation for Biological Models

One of the objectives of international GLOBEC is to promote multidisciplinary research that can contribute to understanding the role of physical effects on marine animal population variability. Data assimilative models represent one approach for synthesizing multidisciplinary data sets. This is an area of modeling that is just beginning to be explored for marine systems and it holds great promise for improving the capability of marine ecosystem models.

Some progress has been made in the application of data assimilation to physical-biological models. Ishizaka (1990) used phytoplankton distributions obtained from Coastal Zone Color Scanner measurements with a circulation and biological models constructed for a coastal region. These data were assimilated using simple data insertion in which the simulated phytoplankton distributions were replaced with the satellite-derived distributions. This study showed that data assimilation improved the accuracy of the simulated phytoplankton distributions. However, it also pointed to several issues that need addressing in future attempts at assimilation of data into biological models.

One important issue arising from this study is the need to develop techniques for updating other ecosystems components when information is assimilated on only one part of the ecosystem. For example, inputting information on phytoplankton requires that the zooplankton, nutrients and other ecosystem components also be updated so as to be in balance with the new phytoplankton distribution. Approaches for doing this are not well developed. Other issues relate to the type and frequency at which data need to be assimilated. This is important because there is a trade-off between the need to provide measurements at sufficient resolution to capture the processes of interest and the cost of obtaining the measurement.

The application of other data assimilation approaches, such as adjoint methods, to biological models needs to be explored. Adjoint techniques offer a way of determining values for little known (and difficult or impossible to measure) biological rates, such as population mortality rates. This approach requires that measurements be available and that the dynamics of the models (circulation and/or biological) be well developed. In this sense, the data assimilation and model dynamics are not independent and the exercise of data assimilation can be used to improve the structure of the model. Also, the use of data assimilation techniques, such as Kalman filtering or optimal interpolation methods, need to be evaluated within the context of biological models.

### B.4.3 Structured Population Models

When developing biological models for secondary production studies, there is always a decision on how much realism to include. At the lowest level, secondary production can be represented in a bulk fashion in which a single undifferentiated zooplankton component is included in the model. However, if more realism is desired then models that allow for age, stage or size-structured zooplankton populations may be required.

One benefit of using structured population models is that this approach allows separation and inclusion of distinct features, such as ontogenetic vertical migration and different feeding strategies. The disadvantage is that a structured population model requires more knowledge in that rates, processes and behavior need to be known for each size, stage or age included in the model. Thus, the use of structured population models for secondary production studies has important implications for the types of measurements that will be needed.

The type of structured population model that is to be used is often determined by the research questions being addressed and the data that are available for model construction. Measurements for many species of marine zooplankton are typically made in terms of animal stage; whereas for other secondary producers (e.g., benthic invertebrates) measurements are usually based on size or biomass. Again, the development and implementation of structured populations models has to be done in conjunction with those doing laboratory and field measurements.

### B.4.4 Summary

The areas in which GLOBEC can encourage development in physical-biological modeling are many. For example, techniques are needed for handling inputs of larger scale processes through boundary conditions and for parameterization of subgrid scale processes. Also, approaches that allow models with different scales of resolution to interact need development. These are just two examples of generic modeling issues that are quite relevant to the success of modeling efforts proposed as part of GLOBEC. Additionally, data assimilative physical-biological models are necessary if the full benefit of multidisciplinary data sets is to be realized.

However, development of other parts of GLOBEC are necessary for the modeling efforts to be successful. Data sets that will allow models to progress are needed and this in turn requires instrumentation advances. Hence, modeling in GLOBEC cannot advance alone. It must be part of a broader initiative.

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## B.5 Topics in Modeling

Michio J. Kishi

### B.5.1 Numerical Model of the Drift of Sardine Eggs and Larvae. Fisheries Oceanography 1—1. Akihide Kasai, Michio J. Kishi, and Takashige Sugimoto

In our present paper, influence of the variability of the pattern of the Kuroshio path, intensity of the wind-driven drift current due to the winter monsoon and the position of the main spawning ground on the retention rate of the larvae in the coastal areas are estimated based on the dispersion experiment. The explanation of yearly recruitment of Japanese sardine in case of considering the three major effects mentioned above are estimated.

Firstly, there is an effect of the short-term variability of the Kuroshio path. In this study, we treated the variability of the Kuroshio path in large scale, but there are observations that the Kuroshio vary its path in a several tens days. Awaji et al. (1991) made a numerical experiment to short-term variations of the Kuroshio, and pointed out that the water exchange takes place between the shelf region and the Kuroshio region over one event of the onshore-offshore movements of the stream axis of the Kuroshio and was estimated to be 6 x $10^{12}$ $m^3$. Such a short-term variation is observed many times when the Kuroshio takes a large meandering path (A-type). This short-term variation could effect the transport of the eggs and larvae.

Secondarily, the effect of circulations in small scales remains an important problem. The effects of small eddies, filaments and circulations in coastal regions were treated as viscosities in this study. In this study, it is suggested that these circulations could affect on the transport of eggs and larvae. Among these problems, the two-dimensional circulation is able to be producible. It is necessary, however, to construct a three-dimensional circulation model in order to produce baroclinic effects.

Thirdly, there is an effect of the wind to be examined thoroughly. In this study, uniform wind stress was encompassing the entire area. But it is necessary to change this stress with space, especially in the area where the winds hit strongly such as Bungo Channel. But we have no precise wind data to be worth to introduce our model. Another effect of wind to sardine eggs and larvae is to give rise to upwelling. The upwelling may supply nutrients, especially in the coastal area. Although we do not know the effect of second or third production induced by this upwelling, it is worthwhile to investigate this effect.

### B.5.2 Prediction of Phytoplankton Growth in a Warm-Core Ring Using a Three-Dimensional Ecosystem Model, submitted to Journal of Oceanography. Michio J. Kishi, Ocean Research Institute, University of Tokyo

In order to simulate the primary production dynamics response to the decay of a Warm-Core Ring 86-B off the east coast of Japan, we developed a numerical model which consisted of three-dimensional physical model (GCM) and we used the same biological model that Franks et al. (1986) did.

According to three-dimensional model, the well-known subsurface chlorophyll maximum was reproduced but horizontal distributions of Chl a. and NO3-N showed different patterns corresponding to different initial conditions of nutrients. This is why the weak vertical velocity in the WCR does not play an important role on the ecosystem but only the light intensity and the balance between uptake and vertical diffusion of dissolved nutrient are important. This result differs from that of Franks et al. (1986). The two WCRs interaction models suggest that a weak upwelling could exist between two WCRs accompanied by baroclinic instability.

### B.5.3 Numerical Simulation Model for Quantitative Management of Aquaculture. Ecological Modeling (in press) Michio J. Kishi, (Ocean Research Institute, University of Tokyo, Minamidai1—15—1, Nakano-ku, Tokyo, 164 Japan), Masato Uchiyama and Yoshiyasu Iwata (Fuji Research Institute Corporation, Kaigan3—2-12, Minato-ku, Tokyo, 108 Japan)

A numerical model is developed for aquaculture management, which consists of four parts:
(1) current simulation model which calculates tidal and wind induced currents,
(2) COD diffusion model which calculates spatial distribution of COD using simulated current,
(3) DO diffusion model which calculates spatial distribution of dissolved oxygen, and
(4) accumulation model which calculates distribution of deposits from aquaculture of fish.

Our model is capable of calculating the detailed spatial distribution of COD and DO by dividing the bay into many grid points. It also takes into consideration the effects of feed and fish in each raft, and the loading of COD from rivers.

Using this model, we can assess the influence of the location or the area of the aquaculture rafts on the ecological and/or environmental system. It is also of practical use in order to obtain a better distribution of rafts in bay areas, or to calculate the basic data for the renewal of licenses of aquaculture business.

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## B.6 Rationale of Ecohydrodynamic Modeling: The Ecohydrodynamic Adjustment

Jacques C.J. Nihoul

As a result of the nonlinearity of the evolution equations, physical processes of all time scales can occur in the sea. Certain, well-defined bands of scales, however,-associated with internal or external forcing mechanisms-, dominate the geohydrodynamics of the marine system.

Geohydrodynamic processes are also characterized by specific length scales. In general, unambiguous dynamical relationships exist between time scales and length scales.

Biogeochemical interactions can also be characterized by specific time scales and the comparison between these time scales and those of hydrodynamic phenomena indicates which processes are actually in competition in the sea.

Obviously at hydrodynamic scales much smaller than interaction scales, very little interaction takes place over times of significant hydrodynamic changes and basically the constituents are transported and dispersed passively by the sea. On the other hand, hydrodynamic processes with time scales much larger than interaction scales scarcely affect the dynamics of interactions over any time of interest. Only those processes which have comparable time scales can significantly affect biogeochemical interactions and act as constraints on chemical and biological systems.

Thus any particular biogeochemical process must be studied in the framework of its "spectral window," subject to the "resonant" geohydrodynamic constraints, embedded in the slowly varying environment of the larger scales and blurred by the (nonlinear) diffusing effect of "subwindow" or "subgrid scale," -turbulent or pseudo-turbulent-, fluctuations.

One can also associate characteristic length scales with chemical and biological processes but this requires consideration when modeling is concerned.

One realizes that the length scales which characterize ecological/biological populations and interactions are basically those of the hydrodynamic processes which have the same time scales as them.

This is evidently a consequence of the nonlinearity of the governing equations and in particular of the advection term which maintains, at all scales, a permanent hydrodynamic stress on the state variables and allows, -in the absence of any significant feed-back-, the structures of the velocity field to be impressed on the ecosystems.

Once the time scales of the ecological processes of interest in a problem are identified, the spectral window is determined. The hydrodynamic processes which are responsible for the transport and space-time distribution of the ecological state variables are the hydrodynamic processes which have the same time scales.

The length scales of these "resonant" hydrodynamic processes are then imparted to the ecosystems by the persisting nonlinear constraint of their embedment in the flow field.

The mechanisms of time scale resonance followed by length scale matching have been called "the ecohydrodynamic adjustment."

### B.6.1 Requests for Three-Dimensional Interdisciplinary Models

From the discussion above, it appears that a three-dimensional model will be needed, at least to reproduce the complexity of the physical background. It is difficult to see, on the other hand, how a simple model could be used to describe ecosystems and biogeochemical cycles. On the one hand, geochemical and ecological processes are strongly correlated with physical processes by the resonant interactions and subsequent scale matching of the ecohydrodynamic adjustment, on the other hand, they live on nutrient supplies which are partly regenerated in the water column, -hence subjected to the caprices of the local hydrodynamics-, partly imported into the system through the boundaries (bottom-sediments, coasts, air-sea interface,...) with a spatial variability which, inevitably, is imprinted on the system's kinetics.

A recent investigation of the Northern Bering Sea's Ecohydrodynamics (Nihoul and Djenidi 1991, Nihoul et al., 1993) has shown, for instance, that the variations in time and space of primary and secondary productions in the Northern Bering and Chukchi Seas and the export of carbon to the Arctic basin were entirely controlled by the persistence of an upwelling in the Anadyr Strait region and the subsequent advection to the Bering Strait and deployment in the Northern Bering Sea of the plume of nutrient-rich water carried along by the Anadyr Stream.

Such interdisciplinary studies also point out to the complexity of the biogeochemical processes which one might have to take into account and raise the question of the feasibility and reliability of sophisticated models. One can see the need of a better three-dimensional understanding of the driving hydrodynamic processes and the sustaining influxes of nutrients and organic material and, in the same time, the desirability of a better-more detailed-representation of the biogeochemical compartments and the translocations between them.

One is obviously limited by computer and man-power and a compromise has to be found, incorporating enough of each discipline's sophistication to be realistic but little enough to keep the model between tractable bounds and provide a feasible, reliable tool to assess global coastal changes, identify the consequences of anthropogenic activities and, dialoguing with scientists from economical and social sciences, provide the bases for marine environmental protection, exploitation of marine resources and management of the marine system.

To limit the scope of a biogeochemical model, one naturally tries to divide the immense biological variability into a limited number of aggregates, -such as phytoplankton, zooplankton ...-, interacting via energy and mass fluxes (in state space) called translocations.

Pioneer ecosystem models were based on simple food-chain concepts with a rectilinear transfer of material from nutrients to phyto- and zooplankton and, further up, to fish. The aggregates were defined by biological speciation (diatoms, dinoflagellates, copepods ...) and the translocations were expressed in mathematical form, assuming generalized prey-predator relationships between the aggregates, still very much reminiscent of simplistic size scale ideas (according to which the smaller prey is eaten by the larger predator ..., e.g., Steele 1978).

The development of marine biology lead to enlarge the concept of food-chains to food-webs, recognizing different competitive pathways in scale-to-scale translocations.

Figure B.6.1 shows, for instance, the Plymouth NATO ASI Consensus Food Web Model. A similar (size-concerned but not size-obsessed) model was proposed by Fenchel (1988), limited to the compartment indicated by the sign $x$. The recent and beautiful model of Maloney and Field (1991) is not very different except that most compartments are renamed, and possibly enlarged to include more of the Plymouth Consensus Model's components. Both models seem to ignore mixotrophs but Maloney and Field's Model has the capacity of taking them into account, in the phyto-and zoo-compartments, in the proportion of their respective autotrophic and heterotrophic activities.

The simplest model one can derive from Fig. B.6.1, which respects the main functional relationships, has (under the assumption that Si and P are not limiting) six state variables, *viz* n1 (nitrate), n2 (ammonium and urea), (phytoactive biomass), z (heterotrophic biomass in the range 2 microns to 2 mm), B (bacterioplankton) and d (detritus and dejection).

This simple model, anchored in the GHER 3D k-epsilon General Circulation Model, has been applied with success, to the study of the Northern Bering Sea's Ecohydrodynamics and may serve as the foothold for the development of biogeochemical/ecosystem models of increasing sophistication (Nihoul 1988, Nihoul et al., 1993).

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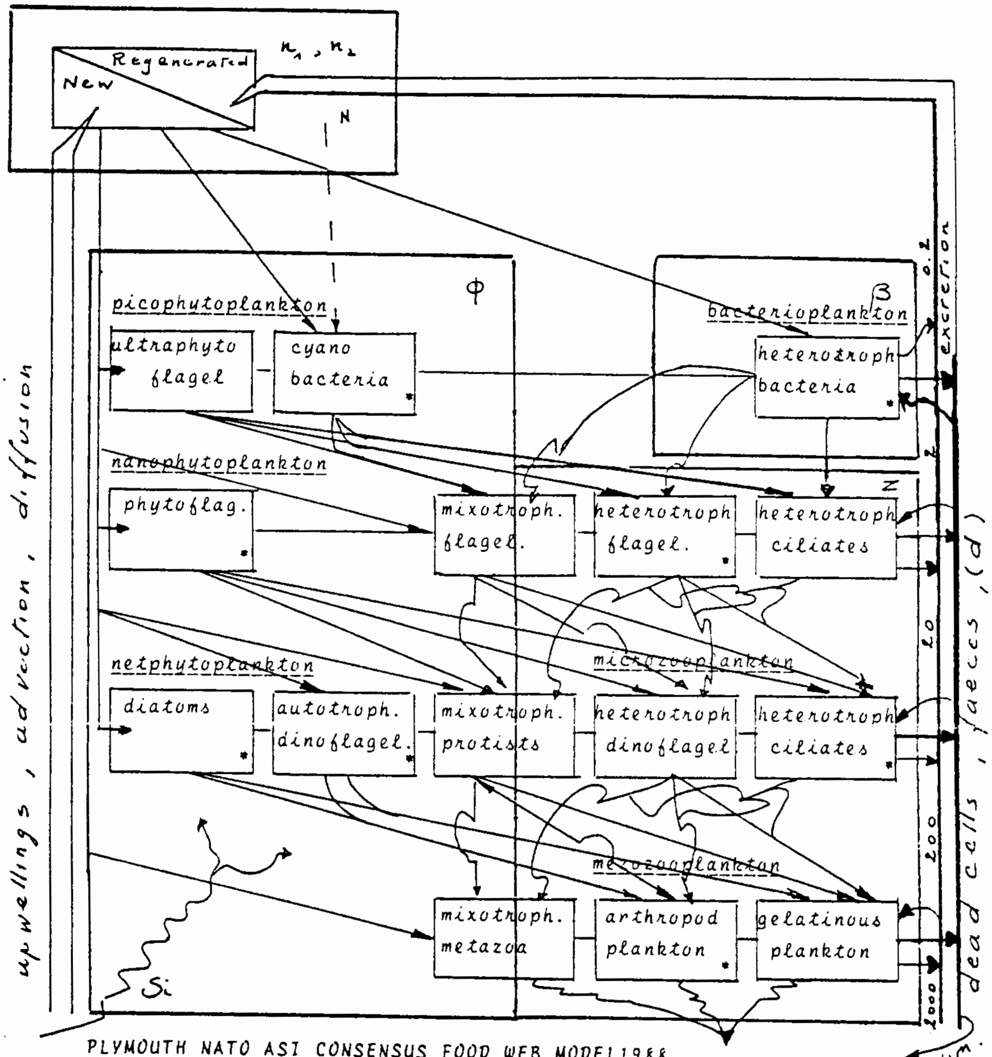
**Figure B.6.1.** Plymouth NATO AST Concensus Food Web Model, 1988.



PLYMOUTH NATO ASI CONSENSUS FOOD WEB MODEL1988
* aggregates in Fenchel's model
underlined are the aggregates in the model of Maloney and Field

## B.7 Problems Relating to Modeling of the Annual Cycles of Phytoplankton and Zooplankton Population Dynamics

Günther Radach

Results from the recent investigation by Carlotti and Radach (1993) simulating the annual and seasonal dynamics of the central North Sea plankton bring features of the dynamics into focus which demand additional observational and modeling efforts.

By coupling a model of population dynamics of *Calanus finmarchicus* with a physical and biological one-dimensional upper layer model simulating the dynamics of phosphate and phytoplankton in the northern North Sea (Figure B.7.1), Carlotti and Radach can model the development of the successive stages and study their role in the dynamics of the ecosystem. The copepod model links the trophic processes and the population dynamics, and each simulation gives the physiological rates and the individual growth within the stages, as well as the share of each stage in the evolution of the population biomass. An annual simulation clearly shows three generations of *Calanus finmarchicus* during the year (Figure B.7.2). The importance of growth of late stages in the whole population biomass is evident. Results of the model with dynamics of phytoplankton and zooplankton are compared with the previous simulations considering zooplankton as a diagnostic variable. In the dynamical version, the peaks of phytoplankton and zooplankton lag by one month due to the growth of the first cohort. When compared with observations in the North Sea, the annual simulation shows too high and broad a phytoplankton bloom and too low biomass of Calanus finmarchicus. A simulation with a higher initial overwintering biomass gives a very different dynamics of the population of Calanus (Figure B.7.3), but not so much concerning the annual biomass. The abundant observations of the Fladen Ground Experiments in the spring of 1976 (FLEX'76) are used to simulate the spring dynamics. Several simulations led to changes in consecutive steps, the initial concept of the modeling starting from the simple relationship phytoplankton, Calanus and ending with the dynamics of the phytoplankton, detritus, microbial organisms, Calanus system. Firstly the simulations demonstrate that grazing by *Calanus finmarchicus* cannot be the only major cause of the limitation of the phytoplankton bloom, because the development of the first stages are too slow, and the last copepodite stages clearly arrive only after the bloom. Secondly, the simulations with phytoplankton as single food source for *Calanus finmarchicus* never permitted to obtain realistic biomasses of *Calanus finmarchicus* population. Pelagic detritutes can provide a sufficient complement for enabling the growth of the population, but for explaining the observed small peak of phytoplankton in the North Sea, the model should take into account in more detail the role of micrograzers which utilize part of the phytoplankton bloom and constitute a trophic link to *Calanus finmarchicus*.

The shortcomings of the model point to several areas where observational evidence is needed: mathematical process descriptions of overwintering mechanicsms are lacking; improved formulations for selective feeding of the stages on different size classes of phytoplankton would make the estimates of the transfer of matter more realistic, when the dynamics of different size classes of phytoplankton were introduced at the same time as microzooplankton.

Radach and Mou (1993) have demonstrated that phytoplankton variability is caused to a large degree by the physical variability imposed on the system by weather variability. It would be of great interest to investigate which portion of the variance of zooplankton stage abundances and biomasses can be explained by weather variability acting of the extended system as proposed above.

*References*

**Carlotti and Radach (1993)**

**Radach and Mou (1993)**

**Figure B.7.1.** Conceptual diagram for the coupled model, combining a 1-D vertically resolved physical and biological model of evenly distributed *Calanus finmarchicus* (0-30 m).

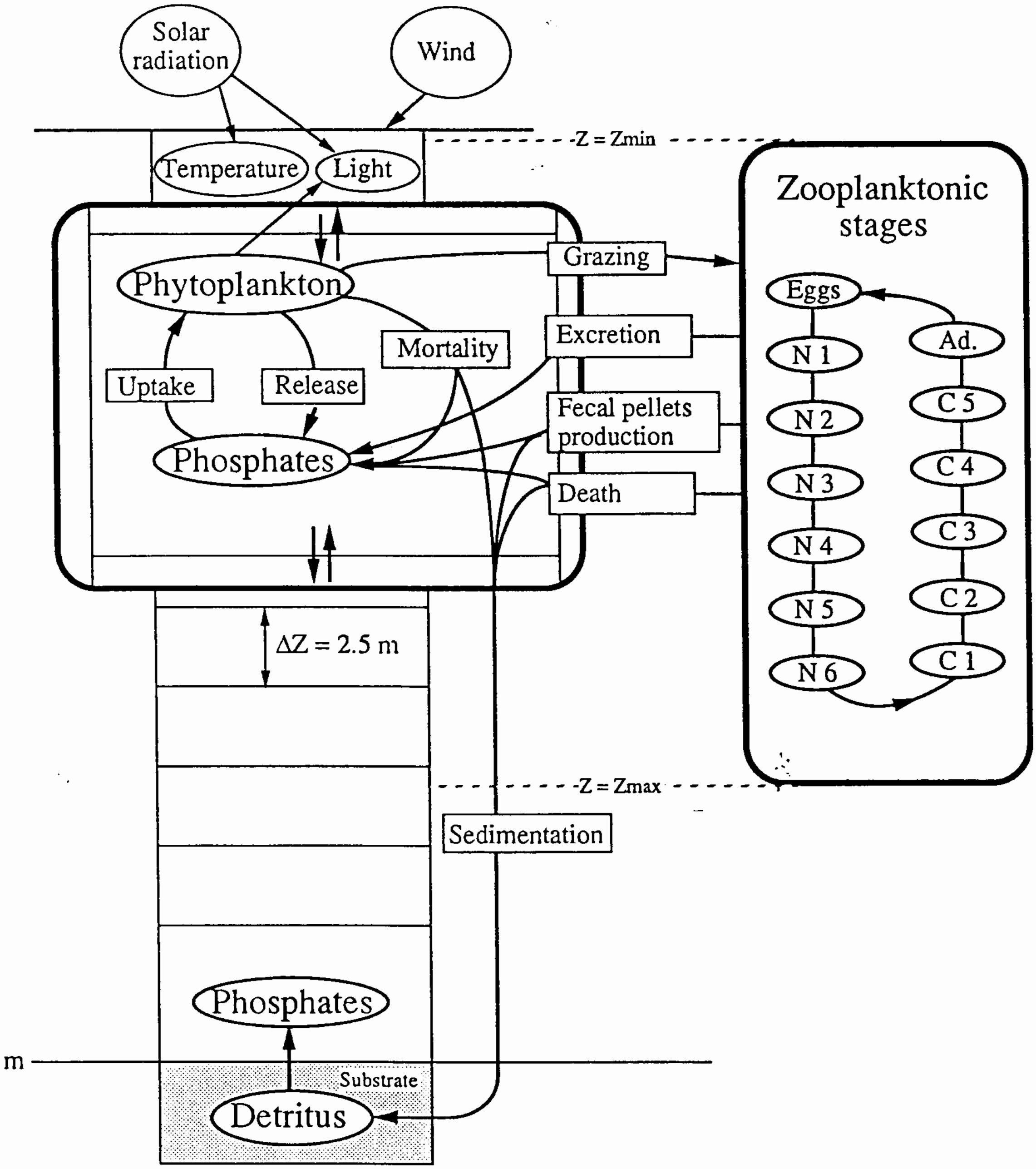


**Figure B.7.2.** Annual standard simulation. Cumulative abundances (A) and biomasses (B) of all stages of *Calanus finmarchicus* for an observed overwintering stock. The stock, being advected into the North Sea, becomes active when a certain temperature and food level is reached.

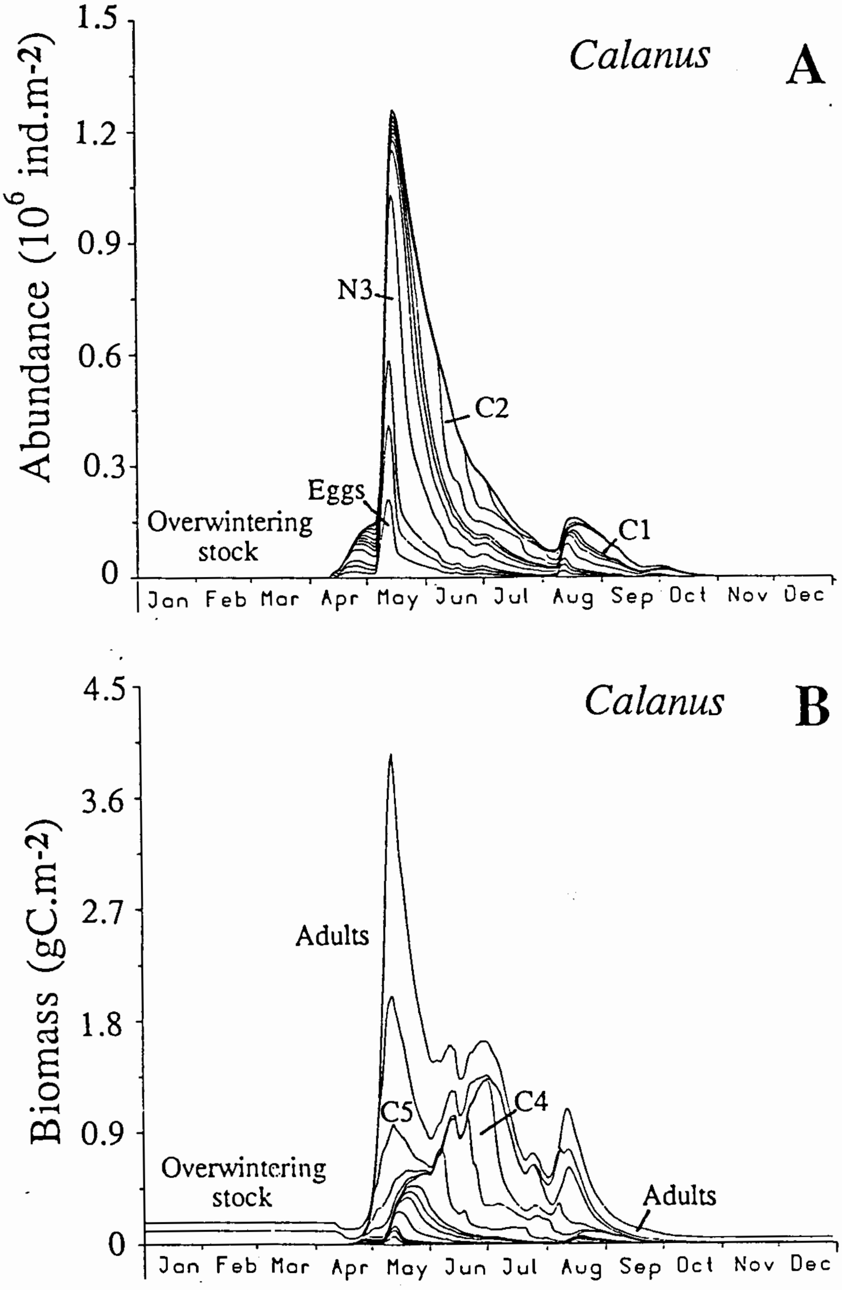
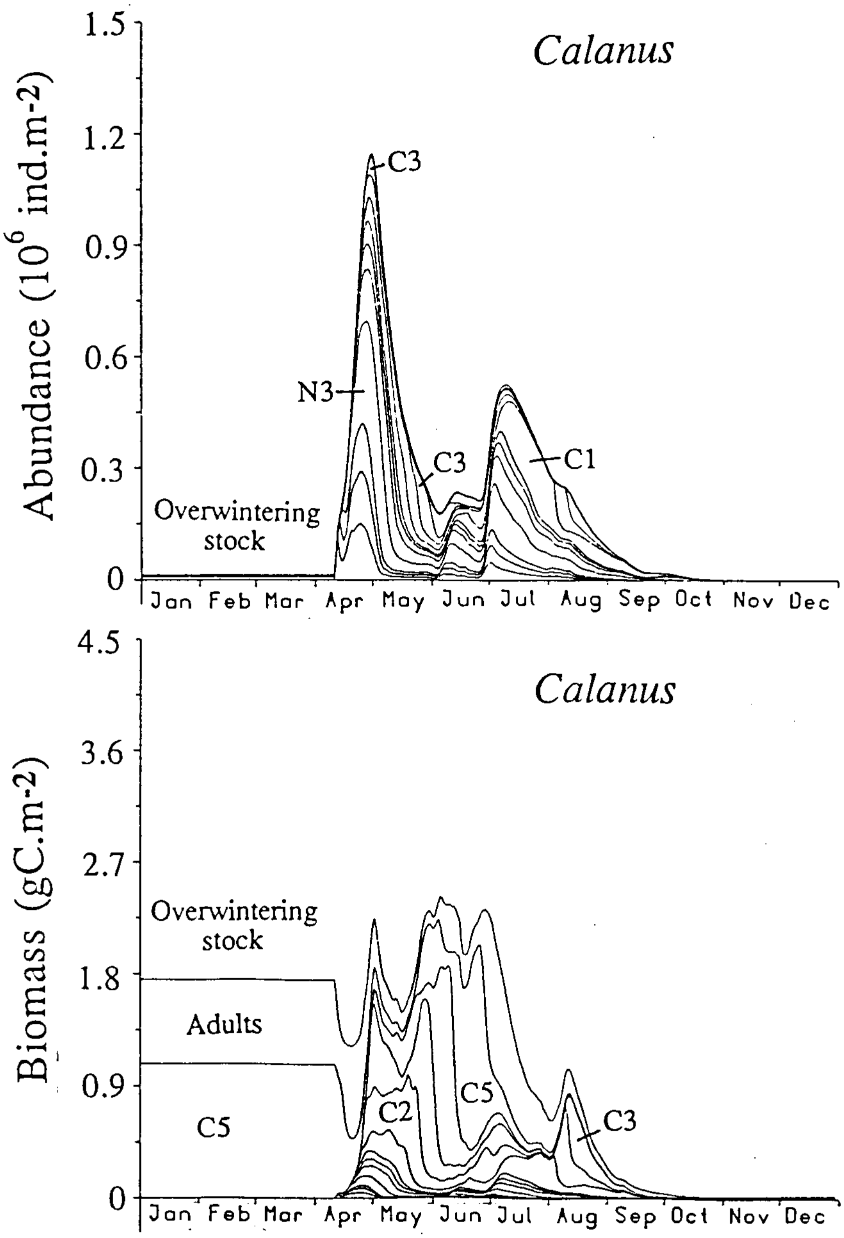


**Figure B.7.3.** Annual simulation obtained with 10 times the overwintering population as in Figure B.7.2. Cumulative abundances (A) and biomasses (B) of all stages of *Calanus finmarchicus*, starting from a high biomass but still low abundance level in April.



## B.8 Physical Processes, Field Estimations and Interdisciplinary Ocean Modeling

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Excerpted from Reports in Meteorology and Oceanography 51, Harvard University

### B.8.1 Interdisciplinary Oceanic Forecast Systems

Realistic oceanic interdisciplinary modeling and forecasting involves a coupled physical/biological-chemical or physical/acoustical system. The three major components of the coupled system consist of the dynamical system, the biological-chemical or acoustical system, and the interfacing scheme. Accuracy, efficiency, and sensitivity considerations require significant research efforts for all components of the coupled system. The overall coupled system is quite complex, but its overall parametric dependencies and sensitivities must be determined, qualitatively and quantitatively. For example, what is the sensitivity of biological and chemical results to both the explicit and subgrid scale physical assumptions made in the dynamical forecast model? Aspects of the physical modeling, such as transports at the base of the surface mixed layer, may need more rigorous treatment for ocean biogeochemical/ecosystem (OBCE) model interfacing than for simply advancing the physics. Many of the large number of parameters which characterize the OBCE model are very poorly known. Thus sensitivity analysis plays a critical role in (semi)quantitative estimates of biological and chemical fields and processes.

The environmental system for forecasting and simulations has subcomponents which serve various purposes and which consist of: data sets; schemes (algorithms) for data manipulation and assimilation; numerical dynamical model implementations; dynamical analysis schemes and applications models. A schematic flow diagram for the interdisciplinary ocean forecast system developed at Harvard and presently in scientific and operational use is shown in Figure B.8.1. The environment in general is characterized: i) by climatological (historical-statistical) data, ii) by a synoptic data base for initialization and updating (assimilation), and iii) by a set of assumptions. For example, large and mesoscale bottom topography can be accurately included directly; whereas, the smaller bottom topographic scales can never be treated in detail and are smoothed or parameterized by a roughness model. Furthermore, the larger topographic scales may be compromised by the representation required by the computational algorithm, such as a step representation (i.e., a discrete depth for each grid location) for input to a dynamical model.

Central to the environmental forecast system of Figure B.8.1 is the dynamical model set component which is characterized both by the explicit physics governing the scales of motion resolved by the computational numerical grid and by the smaller subgrid scale (SGS) physical modeling assumptions. The resolved physical scales may be governed by primitive equation or quasigeostrophic model dynamics. Special physics may be introduced near the surface or bottom boundary or near coasts. The physics adopted should: be adequate for the representation and evolution of the oceanographic features in the environmental region; filter unwanted phenomena; and lead to simple interpretations of results. The interdisciplinary application may put additional constraints on the representation of the explicit physics of the dynamical model or such requirements may be dealt with in coupling schemes.

Other major components of the environmental system are the statistical model set and the data analyses and management schemes. Any realistic field estimate must be based on synoptic observations which generally today are acquired by an efficient mix of *in situ* and remote sensors. The data analyses module of Figure B.8.1 thus includes software components for the treatment of hydrographic, current meter, float, altimetric, etc. data sets. Data is mapped onto regular grids via (multivariate) objective analysis (OA) schemes which interpolate via the minimization of selected expected error norms. These objective analysis techniques have been extended to biological and chemical data sets. Additionally, statistical model components may include empirical orthogonal functions, in the horizontal or vertical, or other modal representations. Of special note are statistical model representations of typical synoptic structures, the feature models, which are utilized to minimize the observational data requirements necessary to achieve a synoptic realization of the state of the system. Analysis, initialization, and data assimilation schemes meld various types of data with different sampling schemes into estimates of fields of interest, input data into models, and produce melded estimates from observations and dynamical model output. Various methods and techniques, some borrowed from meteorology and engineering, are being explored now in oceanography. The assimilation process may be continuous or at set intervals, and various types of *in situ* or remotely sensed data may be utilized in combination. The schematic of Figure B.8.2 represents a sequential assimilation process.

The Assimilation Initialization Scheme (AIS) module of Figure B.8.1 is of particular importance. It may be direct OA data mapping, multiscale feature models, the product of the Fleet Numerical Oceanographic Center (OTIS) (Clancy et al., 1992), etc. The options for data types, processing, and representation afforded by the Harvard ocean forecast system and simulation are sufficiently comprehensive and flexible that the preinitialization/assimilation modules in Figure B.8.1 are grouped together into a Start-Up megamodule (STAR). The Physical (P-Star) module is shown explicitly on the figure whereas the equally complex acoustical (A-Star) and biological/chemical (BC-Star) start-up megamodules are only shown symbolically. Assimilation of biological and chemical data should yield important results in the near future. Obtaining efficient, accurate environmental and multidisciplinary field estimates is technically complex, and although the development of relevant schemes, their validation and the establishment of their sensitivities are still at an early stage, such estimates are now available.

The environmentally forecast or simulated physical fields may be used for a variety of purposes. Two postprocessing modules are shown in the Figure B.8.1 schematic. The first is a dynamical process module which does energy and vorticity analyses via term by term balances (EVA) in a manner consistently matched to the dynamical model utilized. The second is a multipurpose applications module. This involves the further treatment of the physical fields for operational or interdisciplinary scientific purposes and includes such operations as the calculation of sound speed profiles, transports of nutrients, dispersion, etc. Biological and chemical dynamical process analysis schemes, analogous to the physical EVA, are under development to postprocess the fields resulting from OBCE model forecasts and simulations. Additional application models are also under development, including bio-optical.

### B.8.2 The JGOFS 1989 North Atlantic Bloom Experiment

Nowcasts were provided in real time (Robinson et al., 1993) for the JGOFS experiment based on sea surface height information obtained from the Geosat satellite borne radar altimeter. This is depicted on Figure B.8.2. The domain was 540 km by 750 km with the pattern of satellite ground tracks spaced about 1.5 degrees longitude apart as shown in Figure B.8.2a. Each track was repeated every 17 days. The height variation along an early track that served first to identify two of the three mesoscale cyclonic eddies located in the domain is presented in Figure B.8.2b and the location of the "Big" and "Standard" eddies are shown. It is not possible to locate unambiguously the local undisturbed sea level (z=0) height from altimeter data alone (Glenn et al., 1991) and the zero level on Figure B.8.2b was set to depict the two cyclones with additional information from some AXBTs which indicated the presence of cold core eddies. The size and location of the three eddies as revealed by successive Geosat passes is also shown on Figure B.8.2a. From this information and from past knowledge of eddies in the general area (Kupferman et al., 1986; Le Groupe Tourbillion, 1988), the indices of eddy feature models (radius, depth of the thermocline, maximum sound speed, etc., Figure B.8.2c) were evaluated which were used to initialize the QG model. Dynamical adjustment and dynamical interpolation then provide a consistent estimation of the mesoscale fields throughout the domain. This also provides the mesoscale environment for estimation and study of all the physical and related fields in the upper ocean.

In Figure B.8.4 is shown the mixed layer depth and pattern of 25 m temperature on day 138. The biological results (McGillicuddy, 1993) are presented on Figure B.8.3. The evolution of the physical fields is shown on Figure B.8.3 in terms of the vorticity field. The eddies first persist, begin to interact and distort. The interaction between the Standard and Small eddies, for example, elongates and then begins to break up Small. These interactions provide the basis for significant nutrient transports into the upper ocean. Year day 115 is near the start of the bloom, 151 at the end of the bloom, and 181 is well into normal summertime conditions. Nutrient enhancement due to original and prior doming of the isopycnal and isonutrient surfaces in the cyclonic eddies is apparent in the nitrate initial condition on day 115; the phytoplankton is uniform and low at the end of the winter. The vertical velocity of the feature-model initialization is zero. Between days 115 and 151, a bloom occurs that removes nearly all of the nitrate from the mixed layer. The phytoplankton biomass distribution reflects the initial nitrate distribution in that the enhanced nitrate within the eddies has allowed the bloom to proceed much further there. Note the eddy-eddy interactions as shown in the vorticity field. Particularly, the small eddy has interacted vigorously with the standard eddy resulting in transport processes which have significantly increased the nutrient concentration in the center of the small eddy via entrapment. Between days 151 and 180, the increased nutrient in the center of the small eddy gives rise to a local maximum in phytoplankton biomass. The continued eddy-eddy interactions have now produced a nutrient enhancement within the standard eddy which is an order of magnitude greater than the background concentration outside of the eddies. The nutrient transports due to eddy-eddy interactions are in this case much larger than the submesoscale enhancements previously hypothesized to be the most important biological effects of mesoscale motions (Woods, 1988).

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**Figure B.8.1.** Schematic of the Modular Harvard Forecast System.

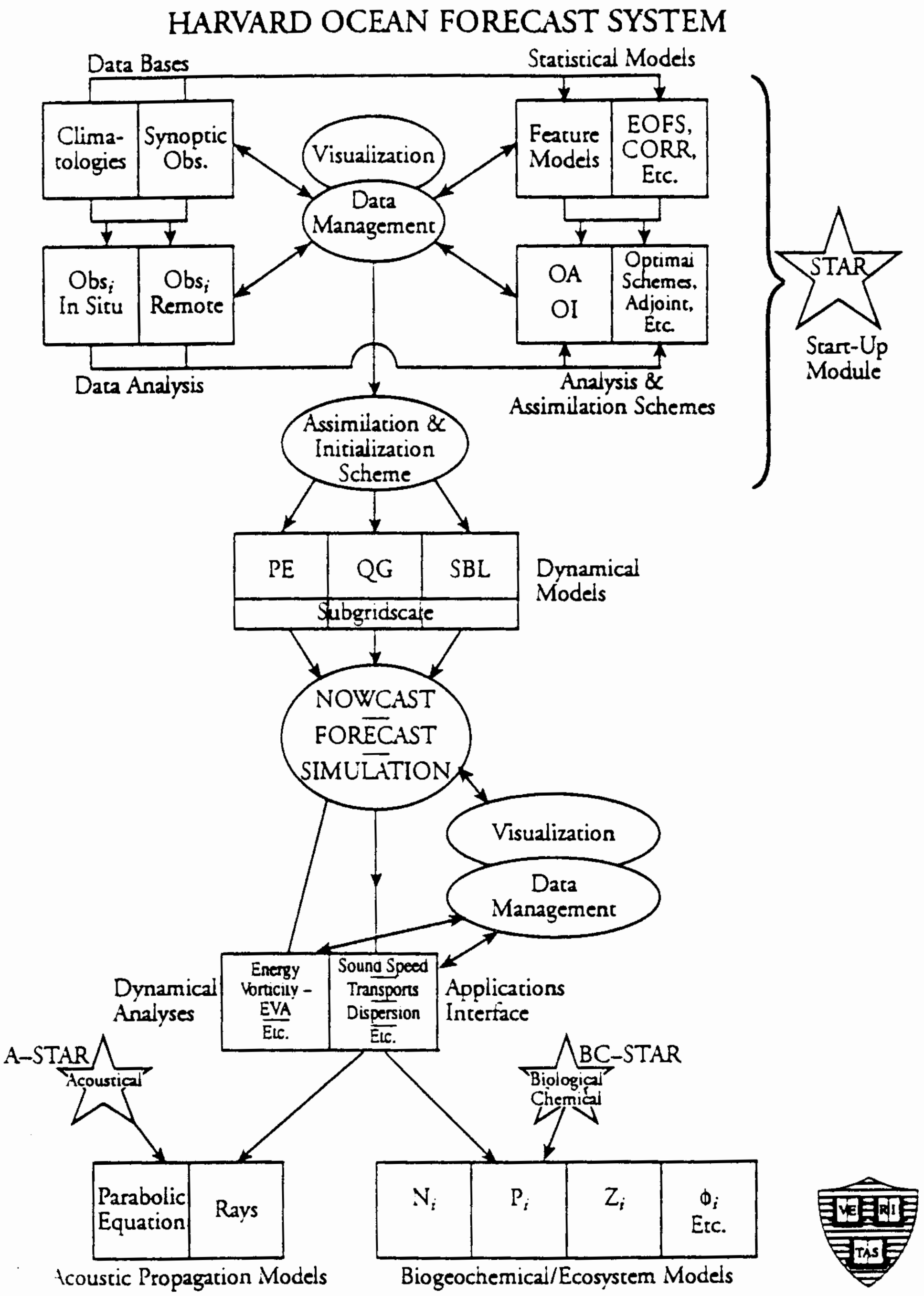


**Figure B.8.2.** JGOFS Spring Bloom Experiment. a) Relative eddy sizes and positions with GEOSAT tracks overlaid; b) GEOSAT altimeter signal along track 122b; c) Eddy feature model.

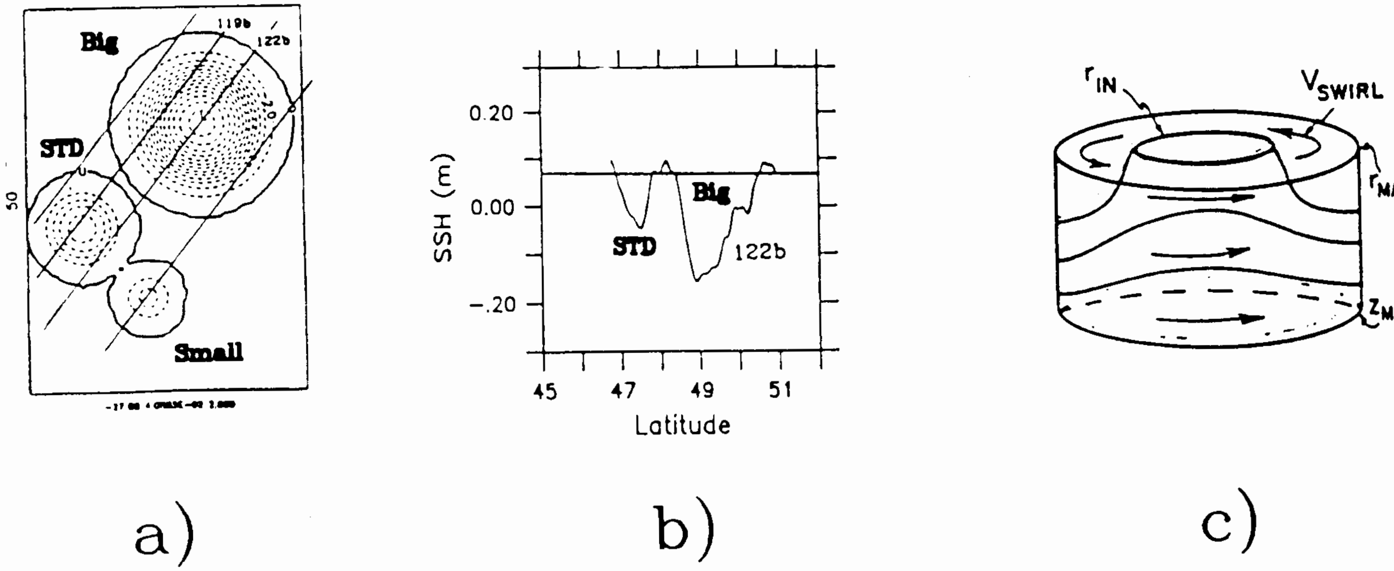


**Figure B.8.3.** Temporal development of physical and biological fields. Day 115 is prebloom, 151 is end of bloom and 180 is postbloom. See McGillicuddy (1993) for details.

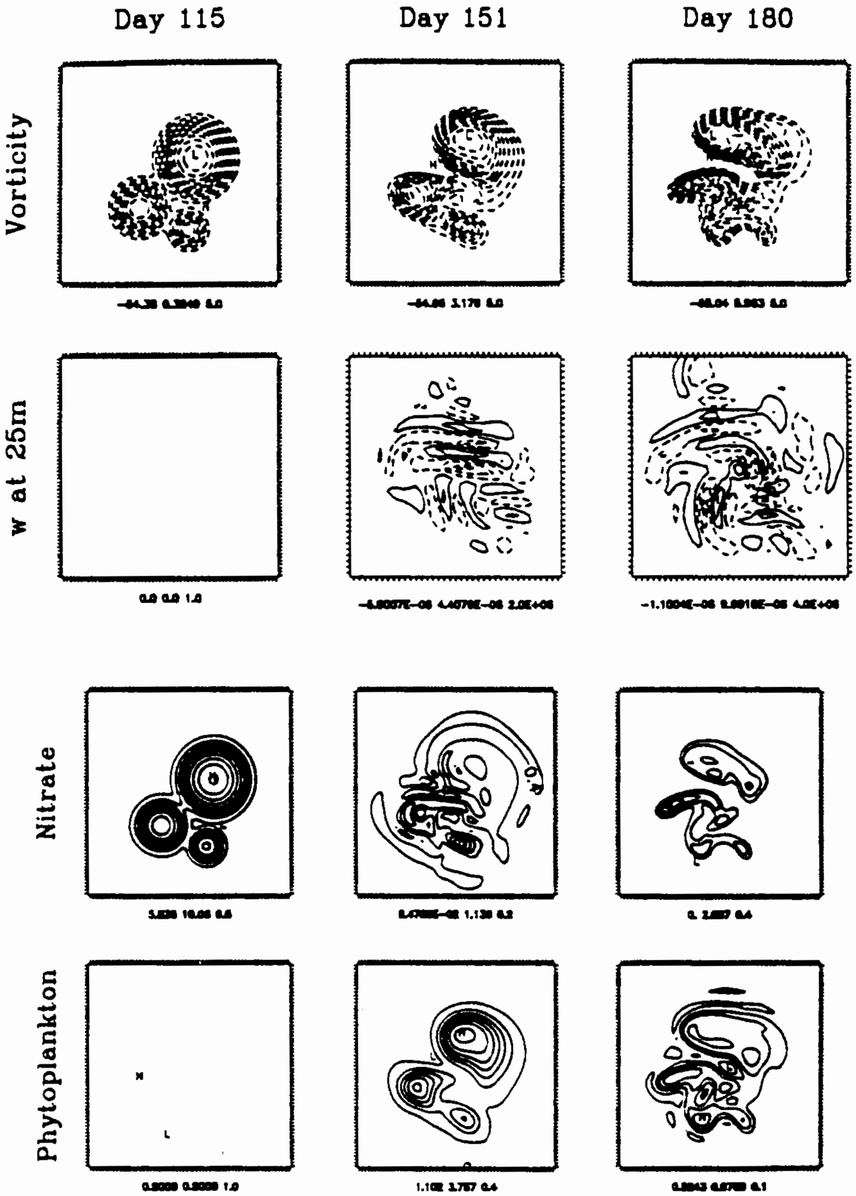
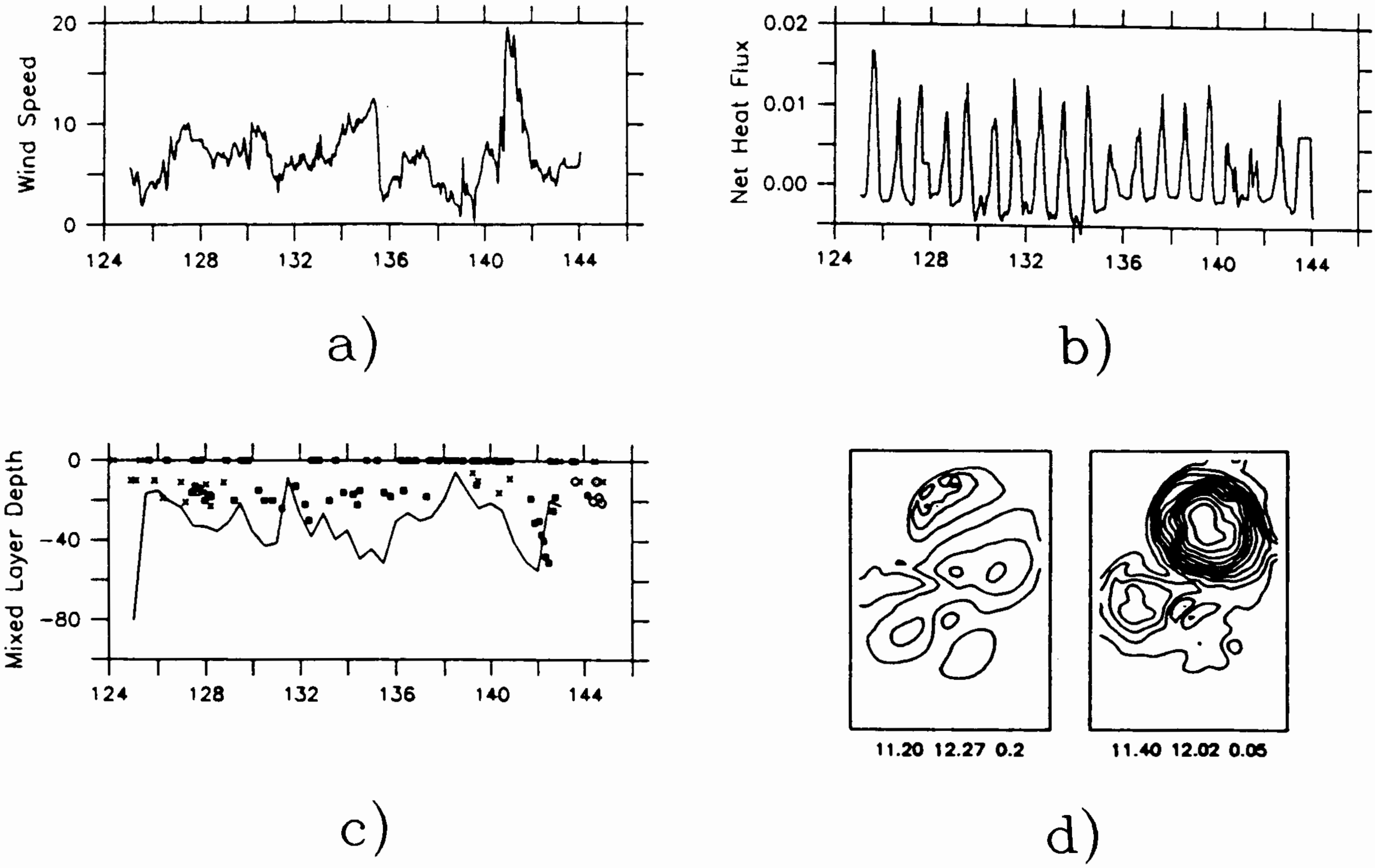


**Figure B.8.4.** a) Wind speed; b) Net surface heat flux; c) The model predicted mixed layer depth with observations superimposed. d) Mixed layer depth (m) and pattern of 25 m temperature °C on day 138. Numbers are minimum, maximum and contour interval values.



## B.9 Population Dynamics/Physical Variability

David Cushing

There are two classes of grazers, copepods and protozoa. The first feed on on particles >5 µm in diameter and the second feed on smaller ones. Hence the distributions of chlorophyll should be separated into two parts. The maximal growth rates of phytoplankton are taken from Eppley's (1979) paper. The work needs repeating to include the growth rates of cyanobacteria.

The protozoa are sampled directly by water bottle and they can be treated as colorless algae; they divide as quickly and their reproduction depends on food. The copepods can be sampled in depth and in time with the Holliday/Pieper equipment, which gives both abundance and size. Because the transducer array can be lowered in the water column, the display is presented as abundance or size in depth and so the vertical migrations in depth can be described. There is a need to identify the animals producing the signal which can be done with optical devices or nets. There is need to develop software to convert the acoustic observations into vital parameters of the population, yielded by sampling in time.

*References*

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## B.10 Sampling and Observation Systems

Tommy Dickey

### B.10.1 Concept

To understand the natural variabilities of the physical-biological-chemical system of the euphotic zone and to predict its forced responses is feasible but lies at the frontier of interdisciplinary science. Such understanding and predictive capability is of importance not only to ocean science, but also to marine resource management because of food-web links and potentially to interactions.

The development of a forecast system for the physical-biological-chemical ocean is now feasible. Such a system is necessary to research physical-biological-chemical interactive processes, to predict and monitor the system, and to assess global change phenomena. It must be a generic coupled model and observational network system which is versatile and relocatable. The interdisciplinary coupled model must be capable of assimilating physical, biological and chemical variables. The observational network should consist of multiple platforms and sensors and key variables must be identified and their fields measured. The system must contain multiscale, nested components. The physical feasibility and its impact on such prototype systems has been demonstrated. To achieve the biological and chemical capability is challenging and demanding and lies at the research frontiers of ocean science and methodology. However, the opportunity represented for accelerated research progress is unique and the field of ocean science can be changed by its accomplishments. It is the only way to achieve the understanding of the physical-biological-chemical ocean and the consequent capability to predict and monitor which is necessary for responsible management of the ocean in the global change context.

## B.10.2 Scales, Processes and Variables

Physical structures and circulation elements in the ocean are now known to occur on many nonlinearly interactive scales. Spatial scales range from small to global and an individual circulation element typically involves multiple scales. The space-time scales of biological processes must be expected to reflect the scale of the physical circulation elements as well as biological processes. Some important biological processes may occur on essentially identical scales or on interactively induced scales occurring, e.g., from a competition between biological behavior and physical transport, which may account for some scales of patchiness.

A number of physical processes for the transport of nutrients, particles and plankton have been identified. These processes are more or less well understood and additional important processes will undoubtedly be discovered via matched-scales research. Horizontal advection by currents and eddies may either redistribute material or entrap material in a fixed location (e.g., George's Bank) or a drifting water mass (rings, eddies, submesoscale lenses). Vertical transport processes occur from the lifting of isosurfaces due to mesoscale/large-scale interactions (eddy formation), mesoscale evolution and interactions (meandering, merging eddies), and propagation processes (planetary waves, eddies, fronts). Additional processes include: Ekman pumping arising from both surface momentum flux and buoyancy flux distributions; coastal, topographic and frontal processes; wind and convectively induced entrainment; breaking internal waves, shear instabilities and double-diffusion.

Prediction and monitoring of the physical-biological-chemical ocean requires the acquisition and utilization of both climatological data sets and synoptic data sets on an ongoing basis. The large number of relevant variables and the hierarchy of scales makes the acquisition of adequate data sets very difficult. Every effort must be made to utilize resources efficiently and to optimally exploit the information content of observations. This can be achieved only if three criteria are met. Firstly, the variables to be measured and modeled must be carefully chosen, and key variables identified. Secondly, an efficient mix of observations from a variety of sensors and platforms must be obtained. Thirdly, the data must be assimilated into models, i.e., field estimated must be obtained from a melding of dynamics and data.

The specification of variables needed for modeling is a crucial planning task. Many of the relevant variables are specified in GLOBEC Reports 3 and 6. However, for general planning purposes, we summarize several of the primary/core variables as follows:

1. Meteorological variables: barometric pressure, wind stress, and air-sea fluxes of heat
2. Physical variables: currents, temperature, salinity, and density
3. Optical variables: PAR spectral diffuse attenuation of light

4. Chemical variables: plant nutrients, dissolved oxygen
5. Biological variables: phytoplankton abundances (by size and species if possible), zooplankton and fish abundances (by size and species if possible), production (primary, secondary, etc.), mortality.

### B.10.3 System Design and Sampling Schemes

Clearly, a nested array of multisensor platforms will be needed and importantly subgrid scale modeling and parameterizations will be needed as well. The wind fields may be sampled using satellite scatterometers. The mesoscale and large-scale temperature and ocean color (for pigment/phytoplankton) patterns can be defined using satellite (AVHRR and Sea WiFS) data. Similarly, surface current can be obtained from TOPEX/ POSEIDON. Acoustic tomography may be employed to develop 3-D current maps. Vertical structure in temperature, currents, bio-optical properties, phytoplankton and zooplankton abundances can be determined from moored arrays and drifters (e.g., fixed depth multivariable systems or multivariable profiling systems). Importantly, data obtained from these various platforms can be telemetered in near real-time for data assimilation modeling. The spatial sampling resolutions from satellite platforms are fixed. However, the selection of the optimal number and placements of moorings and drifters will require input based on numerical model results. Furthermore, in order to sample subsurface features and phenomena on scales from 10s of meters to the full extent of the observational domain will require ships which can tow a variety of sensor arrays. At some point in the future, this function may be accomplished with AUVs, however, this is not likely within the next 5—7 years. There is also a need to develop subgrid scale parameterizations and to directly observe predator-prey interactions, so a limited number of highly instrumented and/or ship occupied sites will be needed.

### Sampling by Scale

The successful execution of the Observing System Simulation Experiment (OSSE) will require a judicious choice of sensors and sampling platforms. Undersampling is inevitable on virtually all scales in space and times. Synopticity of sampling is yet another critical concern. In addition, cloudy conditions will often eliminate satellite SST and color imagery, thus it is important to have adequate *in situ* data for the assimilation models.

1. Large-scale sampling: This sampling will be best accomplished via satellite (AVHRR, TOPEX/ POSEIDON, Sea WiFS, scatterometers, etc.). With these platforms, near surface physical and phytoplankton dynamics may be deduced. However, no useful information of direct relevance to higher topic levels may be obtained from satellites at present. Drifters may be useful for providing at least some basic physical and biological data; selections of key variables for this application must be made. Ships towing nets as well as acoustical and optical sensors appear to be the only feasible platforms for obtaining higher tropic level data at present.

2. Mesoscale sampling: The satellite platforms described above are useful for the mesoscale down to scales roughly on order of several kilometers. Towed platforms are must useful for sampling down to horizontal scales of 10—100 s of meters and vertical scales of a few meters of less. A broad suite of acoustical and optical sensors may in principle be interfaced with these platforms.

3. Local sampling: Moorings may be used to obtain time series on very small time scales for long time periods. A multiplicity of optical and acoustical as well as physical and chemical sensors may now be deployed from moored systems. There remains a need for autonomous profilers which can provide key data with good (say ~12 m vertical resolution); however, these should be available in the next few years.

## Appendix C. Agenda and Participants

### C.1. Agenda

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Monday, 12 July

0830 Introduction and Agenda - Robinson
0840 Overview of GLOBEC.INT - Rothschild
0900 Review of work in progress and introduction of issues Denman, Fasham, Franz, Hofmann, Kishi, Nihoul, Nival, Radach, and Robinson

Related working group presentations

1600 Population Dynamics and Physical Variability (PDPV-WG) - Cushing
1630 Sampling and Observation Systems (SOS-WG) - Dickey
1700 General Discussion

Tuesday, 13 July

Scientific Discussion Topics (leaders indicated)

The organization by scales has been chosen. Each leader should try to discuss: • Physical structures and phenomena; • Biological and chemical processes, rates and conceptualization; • Forcing functions, boundary conditions and climate change; • Synthesis and scale interactions and linkages.

0830 Small Scale Processes and Modelling - Denman
0915 Mesoscale Regional and Coastal Processes and Modelling - Radach
1000 Large and Global Scale Processes and Modelling - Fasham
1100 Numerical Methods and Data Assimilation - Hofmann
1145 Observations, Experiments and Data Sets - Robinson

Functional and Logistical Discussion Topics

1400 Models and Methods: Development and Exchange (modularity, intercomparison and validation) - - Robinson
1445 Communication and cooperation with other working groups and programs - Robinson
1600 Organization and convening of working groups

Wednesday, 14 July

0830 Working groups reconvene and write reports
1100 Interim plenary discussion
1400 Working groups reconvene and write reports
1600 Final plenary discussion and submission of reports

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## C.2. Participants

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