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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Environmental Data Service

Proceedings of the NMFS/EDS Workshop on Climate and Fisheries April 26-29, 1976

Meetings held at the
CENTER FOR CLIMATIC AND
ENVIRONMENTAL ASSESSMENT
Columbia, Mo.

Washington, D.C.
October 1976

U.S. DEPARTMENT OF COMMERCE

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FOREWORD

The National Marine Fisheries Service-Environmental Data Service Workshop on climate variability and its impact on fisheries was arranged because of the increased attention being placed on the relation between climatic variability and variations in living marine resources.

A particularly salient point to come out of the workshop was the apparent connection between biological, oceanographic, and meteorological events widely separated in space or time. Examples presented by the participants show that the warm sea surface temperature anomalies in the eastern north and tropical Pacific are often linked to cold anomalies in the Gulf of Mexico and western north Atlantic. The location of these thermal anomalies in the North Pacific apparently influences the heights of the 700-mb pressure level and contour patterns, which in turn control the movement of winter air masses over the North American continent.

A specific example occurred in 1958 when an el Niño off the west coast of South America coincided with a trough over the eastern U.S. Cold continental air masses penetrated far south of their usual winter location and caused colder sea surface temperatures in the Gulf of Mexico, resulting in reduced survival of larval shrimp in the Gulf and increased survival of larval menhaden along the east coast. Also, warmer than normal ocean conditions on the California-Oregon coast resulted in several warm water species being taken commercially for the first time since the early 1900's.

Some of the papers presented at the workshop described efforts currently underway to model ocean-atmospheric circulation and interaction, others, the state of the art in biological modeling. It became apparent from the interaction between speakers that we are moving toward more sophisticated models relating air-sea interactions to fishery yields. The National Marine Fisheries Service, with its responsibility under Extended Jurisdiction, is charged with developing realistic quotas that must be based on accurate predictions of future stock size. EDS's Center for Climatic and Environmental Assessment has the responsibility for developing climate/resource models and in doing so provides energy consumption estimates and crop yield models. The interaction between ocean conditions and atmospheric circulation can directly influence the yield of crops and fishery products. Our ability to make forecasts of these variables will provide accurate estimates for setting fishery stock quotas and predicting crop yields, both of which are of critical importance to the nation.

The ideas exchanged in this first workshop on the interaction between climate and marine resources will lead to closer working relations between EDS and NMFS. We hope this will set the stage for more exchanges relating climate variability with this and other environmental disciplines dealt with by NOAA.

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PROCEEDINGS OF THE NMFS/EDS WORKSHOP ON
CLIMATE AND FISHERIES, APRIL 26-29, 1976

EXECUTIVE SUMMARY

A joint National Marine Fisheries Service (NMFS)-Environmental Data Service (EDS) workshop on climate and fisheries was convened at the EDS Center for Climatic and Environmental Assessment (CCEA) at Columbia, Missouri, April 26-29, 1976. The purpose of the workshop was to explore areas of potential mutual interest, to identify specific projects in which joint efforts might be beneficial, and to assess areas of joint operational capability. National Oceanic and Atmospheric Administration participants included representatives from NOAA headquarters, NMFS, EDS, National Weather Service (NWS), National Environmental Satellite Service (NESS), and Environmental Research Laboratories (ERL); in addition, representatives from the Scripps Institution of Oceanography and the Oregon State University participated in the workshop.

Workshop discussions centered on two major subject areas: 1) cooperative modeling efforts focusing on the impact of large-scale climatic variation on global protein potential and selected regional fisheries, and 2) potential use of CCEA climate assessments by NMFS. Over the course of the workshop, a general awareness developed that the atmospheric forcing that triggers events such as El Niño was also evident simultaneously in other anomalous fisheries events, highlighting the global, rather than local, impact of the atmospheric impulse.

WORKSHOP RECOMMENDATIONS

Workshop sessions stimulated clarification of mutual interests and resulted in identification of some basic steps that need to be taken to ensure the optimum sustained return from the marine protein potential. During the workshop, the following four recommendations were developed; the organizations involved and the man-years (MY) of work projected are indicated.

1. Model Development (NMFS, 2 MY; EDS, 2 MY)

a. A cooperative effort between NMFS and CCEA should be initiated to develop a marine bioclimatic model for yields of major populations of shrimp and plankton-feeding fish (herring, sardines, anchovies, menhaden). Initial efforts will be directed toward regional studies, later to be expanded into global assessments.

b. A global model should be developed to estimate the biological production rate at the base of marine food chains, based on a global chlorophyll data base to be developed from satellite and sea-truth data.

2. Model Catalog (EDS, 1 MY)

A time series data base should be developed of physical, chemical, and biological data, of time and space scales commensurate with the variability of Fisheries phenomena in question. Special emphasis should be given to the maintenance of existing observational data bases.

3. Assessment (NMFS, 0.5 MY; ERL, 1 MY; NWS, 1 MY; NESS, 1 MY)

A joint effort should be undertaken to develop an operational program to forewarn of episodal events such as an El Niño (e.g., using the Quinn Southern Oscillation Index) or anomalous Arctic ice conditions.

4. Model Catalog (EDS, 1 MY)

Documentation on available models should be developed that will list: title, authors, type, data base, boundary conditions, equations, conceptual flow chart, program language, computer power required, availability of programs, uses, etc.

Subsequent to the meeting, the working group and workshop chairmen further suggested that priorities for action on the recommendations be according to the numbers assigned to the items listed above, and that action be as follows.

Modeling efforts should be initiated at once (FY 77) with NMFS and EDS each providing resources. Activities would be conducted at the CCEA office in Columbia, Missouri, where personnel can work together on model development. Interest has been expressed by several NMFS fishery biologists involved in modeling in spending some time with the CCEA modelers. We recommend this be accomplished by rotating temporary duty assignments.

Appropriate staff from both MLC's should work out the details for initiating the first priority programs and planning for the others. We recommend that the NMFS Fishery Oceanography Coordinator and the EDS Special Assistant for Marine Science provide staff support and coordination efforts in this area.

REPORTS OF WORKING GROUPS

I. ASSESSMENT OF LARGE-SCALE CLIMATE VARIABILITY

It is now widely recognized that annual food production, both from land and the oceans, is subject to significant variation because of climatic variability. The development of models showing these relations are dependent upon historical data on such variables as air temperature, cloud cover, sea level pressure, sea surface temperature, etc. Within NOAA available historical data permit description of climatic variability in the past. This has been done to a limited extent by CCEA and NMFS for certain regions and limited time periods. Neither NMFS, CCEA, nor any other NOAA component has the capability to predict future climatic change with reasonable accuracy. Though this capability is desirable, it is not considered a critical deficiency in

development of food production-environmental models. Nevertheless, the bounds of future variability can be established from long time statistics.

Areas of cooperative work between NMFS and CCEA could include meteorological data base development, global monitoring, and regional studies.

The following studies are proposed:

1. Gulf of Mexico and Eastern Seaboard. The coastal area of the Gulf of Mexico and eastern seaboard are of immense fishery interest because of the dependence of major species, e.g., shrimp and menhaden, on estuarine areas for nursery growth. These are areas of large environmental change from year to year, especially in winter, because of changes in atmospheric circulation over North America. The opportunity exists for NMFS and CCEA to cooperate in studies defining this relation with data now available. These studies should consider the effect of variations of rainfall and consequent runoff into estuarine areas as well as temperature changes in estuarine areas due to changing atmospheric circulation.
2. Arctic Ice. The Bering Sea is one of the richest fishery areas of the world especially with regard to groundfish resources. This area has undergone significant climatic change since 1970. Though groundfish resources are more resistant to effects of climate variability than pelagic resources, continuation of the cooling trend might have some effect on fishery production, especially if the Bering Sea icepack now extending farther south than normal should penetrate even farther south. NMFS and CCEA, with the assistance of other elements of NOAA, should explore the development of information on the retreat and advance of the Arctic icepack. The CCEA Assessment Center, working with input from participating NOAA MLC's, could provide summary information on the region to interested users.
3. Climatic Fluctuation-El Niño. Variations in the anchoveta population off Peru may be related to climatic variations in the Southern Hemisphere. CCEA with the assistance of NMFS should explore development of an operational program using the Quinn indices which have been developed and tested, e.g., Quinn's Southern Oscillation Index, to be able to forewarn of the possible onset of El Niño and the attendant economic consequences.

II. EPISODAL EVENTS

Episodal events for consideration in the marine environment are those having significant impact on marine production and which are aperiodic and not predictable with established observational systems.

Examples of such events are El Niño, western boundary current meanders and eddies, storm surges, freshets and flood plumes, climatic fluctuations (Multi-year), climatic change (multi-decade), fish kills, and blooms of micro-organisms.

The various time and space scales of these events are shown in the following chart:

So long as such events are unpredictable, a monitoring program must be conducted to record and describe them and to guide further studies of the events directed toward acquiring sufficient understanding to model and predict their occurrence and impact.

III. REAL TIME OPERATIONS

Definitions

The term "real time" means different things to different people; precise definition depends upon the nature of the problems to be solved. Time steps and space dimensions vary significantly between the atmospheric and oceanographic elements; each group must be addressed in a different matrix. In both matrices the following questions must be addressed:

How often are decision functions exercised?

What is the structure and nature of the real time services required?

How are the data to be used?

What is the minimum acceptable data set required to describe the feature in question?

What reporting and summary intervals are appropriate to the phenomenon under study?

Data

Real time data appear to fall into two convenient categories:

1. Meteorological. The present time-spaced protocol seems appropriate, in both frequency of observation and in number, to describe events on a synoptic-global scale. System deficiencies lie in (1) late delivery of analyses and forecast data; (2) loss of data in the reporting-analysis-dissemination system; and (3) the need to fill voids in both the time and space dimensions. Weather-related uses require a minimum 6-hourly synoptic reporting; climatic scale events can be described by integration through progressively longer intervals of time.

2. Oceanographic. The time steps depend on the size of the area under study. Boundary zones (e.g., coasts, bays, estuaries, and ocean fronts) require data on time scales ranging from hours to days to weeks to accommodate tidal cycles and meteorological forcing. Offshore and oceanic regions (e.g., current systems, gyres) require data on time steps ranging from days to weeks to months to seasons.

No agreement was reached as to what constituted appropriate space dimensions. However, it was suggested that boundary zones might require observational grid spacing on the order of tens of kilometers while offshore (oceanic) regions might be described by grid intervals on the order of hundreds of kilometers.

Other data may be required in "real time" to complete an adequate model of a fishery system, but they may not necessarily be related to physical dynamic processes. These data may be of social, political, or economic character, and may be extremely critical to the development of accurate models. Determination of appropriate time-space steps must be made on a case-by-case basis (examples include: salmon fisheries in bays and estuaries; highly migratory species such as tuna; nonmigratory species such as anchovy, sardine, shrimp, etc.). Boundary conditions, physical limits, ranges of variation, and extreme limits must also be described on a case-by-case basis.

IV. OCEANOGRAPHIC MONITORING REQUIREMENTS

Principles and Objectives

Oceanographic processes are extremely complex and incompletely understood. Because of the character of the oceanic system, man is unable to observe and describe the ocean environment cheaply. His working knowledge of physical and biological processes is little more than skin deep, and his technological capacity to probe below the upper-mixed layer is limited. Nevertheless, he can learn much about the variability of oceanic systems if he utilizes fully the relatively inexpensive observational data base already in existence.

Oceanographic monitoring and measurement programs should be process-oriented. Data should be accumulated on time and space scales commensurate with the natural variability of the phenomenon in question. Measurements fall into the following three general categories:

1. Physical Measurements. Physical parameters are generally understood and technical basis is well tested. Such measurements are least costly to obtain. However, there is need to:

a. Maintain a continuum of existing measurements at selected locations (e.g., standard meteorological measurements at island and shore stations, shipboard meteorological and oceanographic observations, etc.);

b. Broaden the scope of measurements and expand the data base to meet the following time-space dimension requirements:

Low-resolution; large-scale (global)

High-resolution; small-scale (regional and local); and

c. Identify and concentrate on oceanic "centers of activity" that require special monitoring schemes.

2. Biological Measurements. Measurements are least numerous at critical points in the lower trophic zones. We lack realistic operational models of marine ecosystems, particularly for those parameters permitting evaluation of physiological rate processes. These measurements are more costly to obtain than physical measurements.

3. Chemical Measurements. Measurements are fragmentary at best and generally not taken synoptically. Techniques are variable, manpower-intensive, and costly to employ. However, dynamics of marine productivity cannot be deduced or forecast until the biochemical interactions are incorporated into the system model. These measurements are the most costly to obtain.

To meet the goals outlined above, we must also:

Resolve the problems of scale for oceanographic parameters;

Reconsider and endorse cheaper, more "pedestrian" techniques, where experience is proven;

Develop new justifications for maintenance and support of observational schemes where the original basis has been lost or superseded; and

Search for oceanic climate integrators in the living marine resource community (e.g., shrimp, menhaden, anchoveta, anchovy, etc.), taking the simplest cases first.

Data requirements now recognized widely among the working oceanographic community accumulate to a long, expensive list. Nevertheless, orderly pursuance of the program outlined above will permit an incremental approach to the description of oceanic processes and their prediction in accordance with society's needs.

V. PRODUCTS AND USERS

Two tasks were identified by the Products and Users Group:

Identification of the products likely to stem from joint NMFS and CCEA research efforts, and

Identification of possible users of the information generated.

Products

The major product of a joint NMFS-CCEA research effort will be a better understanding of the effects that environmental factors have on the state of stocks, stock behavior (migration and aggregation), recruitment, and survival. Joint NMFS-CCEA efforts could narrow the list of factors to be monitored.

Herring, anchovy, sardines, and other herbivorous fish were indicated as species subject to variation caused by climatic change. Species used in the production of fish meal were isolated as a group to concentrate on because of their worldwide economic importance.

Standardization of product dissemination procedures also is indicated.

Users

Five groups were identified as potential users of the information generated: Fishery management councils; teams set up to establish international agreements; industry; high-level government planning and division members (i.e., State Department, Department of Commerce, etc., concerned with International Policy); and fishermen.

VI. MODELING

Introduction

Marine fisheries bioclimatic models are following the historical trend, beginning as empirical-statistical and becoming increasingly predictive-deterministic. The most successful marine modeling efforts have occurred when long-term time series have resulted from monitoring, frequently begun for other purposes.

Marine fisheries bioclimatic models are constructed for the same reasons that modeling efforts are usually undertaken: to make predictions, to affect decisions, to construct better models by testing predictions, and to tell us what to observe, and where, when, and how to make the observations.

Recommendations

1. A clearing center for data on available models should be developed. The data should be included in a catalog that will list title, authors, type, data base, boundary conditions, equations, conceptual flow charts, program language, computer power required, availability of programs, uses, and other pertinent information.

2. A cooperative effort between NMFS and CCEA should be initiated to develop a marine bioclimatic model for yields of major population of plankton-feeding fish (herring, sardines, anchovies, menhaden).

3. An accelerated effort should be made to validate the Ekman-transport geostrophic-flow relationship under different time scales and physical boundary conditions. Since a variety of ocean experiments have been performed, the results of these activities must be summarized and analyzed first.

4. As a global data base for distribution and abundance of chlorophyll is developed from satellite and sea-truth data, a global model should be developed to estimate the biological production rate as the base of marine food chains.

VII. DATA BASES

The initial development of models for herring-like fishes and primary productivity was agreed upon. Data bases were discussed in terms of their direct use in models. For the sake of discussion, data bases were divided into meteorological, physical-chemical, and biological.

Although meteorological data are available within NOAA for development of long time series data bases for use in development of production models, much remains to be done in this area. Both NMFS and CCEA should continue to develop time series data bases and whenever feasible take into account needs of the other agencies in this work. For example, the historical sea level pressure data base now under development by CCEA for land areas could be expanded to include the oceans for use by NMFS.

Long-term physical and chemical data bases which are consistent in time, space, and technique are necessary, particularly along the coast of the U.S. Four additional physical data bases were specified as having immediate use: ambient light at the sea surface and extinction coefficients as measures of energy, ship drift observations to provide insight into flow patterns, and bottom temperature data as a factor influencing demersal fish.

Standardized chemical data bases on O,S,N,Si, and P should be maintained, but the difficulty of establishing coherent data bases of other chemical nutrients was recognized. The group supported the efforts of NODC to encourage conformity and screening of data. Salinity sampling at the surface was discussed, but no recommendation was proposed.

The need for chlorophyll data was recognized. A chlorophyll data base from satellites should be utilized, as observations become available, to provide a coarse estimate of productivity on a worldwide scale. The data should be used in conjunction with data from ground measurements.

The group agreed that there is no immediate capability to establish bases for zooplankton (i.e., non-fisheries above the first trophic level). The need exists for inventories of data files, their time and space limitations, and contact points for additional information.

PRESENTATIONS

MODELING OF THE IMPACT OF CLIMATIC VARIABILITY

FOR THE PURPOSE OF ESTIMATING GRAIN YIELDS*

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INTRODUCTION

Two basic approaches to modeling the impact of meteorological variability on crop yields are:

The physiological approach--an attempt to describe the detailed impact of meteorological variability on biological-physical processes that occur within a typical plant or a plant canopy, and

The statistical approach--an attempt to use a sample of yield data from an area, such as an experimental plot, a crop district, a state, or a province, and a sample of weather data from the area to produce estimates of coefficients in the model by a regression technique.

THE PHYSIOLOGICAL APPROACH

The physiological approach is basically *causal*. Ideally, such a model should be based on detailed, time sequential knowledge of the biological-physical processes which take place within the plant and in the immediate atmospheric-soil environment. This knowledge, in quantitative form, is the model. Such a model serves as a scientific tool for studying the impact of climate change, deliberate genetic "engineering" leading to better adaptation of a crop to a given range of climatic conditions, estimating crop yields, or estimating the phenological progress of a crop under given weather conditions.

While investigators in many disciplines have developed an impressive body of detailed quantified knowledge of the many complex processes that occur within plants and within the immediate environment of plants, I am not aware of a current model based directly and only on such biological-physical knowledge.

*Extended abstract of paper originally presented at the Third Conference on Biometeorology of the American Meteorological Society August 18-23, 1975, College Park, Maryland.

Many of the models in the literature are consistent with one or more causal mechanisms within the crop and its immediate environment, but coefficients in the models are often the result of regression-correlation analysis of sample greenhouse or experimental plot observations.

The major advantage of this approach is that it is based on knowledge of causal relationships. The major disadvantages are:

- (1) The knowledge of causal relationships between weather events and biological/physical processes within the plant and the plant canopy is incomplete; and
- (2) detailed measurements for estimating the coefficients in a physiological model are limited to comparatively small sample plots and short sample periods. The problem of extending the results of physiological modeling for specific locations to aggregated estimates of crop progress or of final yield over commercially important large regions has not been completely solved.

THE STATISTICAL APPROACH

The statistical approach is *correlative*. Here, the investigator usually has access to a series of yield estimates from an area which may be as small as a research plot or as large as a whole country and a sample of weather data from the same area. Coefficients for this kind of model are obtained by use of a regression technique applied to the yield and the weather data.

At worst, the regression work proceeds as a "cut and try" effort to look at almost all possible specifications for the weather variables in the model. At best, the specification of the model is consistent with the most complete knowledge of biological and physical processes.

The chief advantage of the statistical approach is its feasibility. Usually it is possible to obtain sample weather and yield data from a desired geographical region and to gain access to a regression routine that requires only minimal programming efforts.

Some of the disadvantages of the statistical approach are:

- (1) The investigator nearly always has to use yield and weather data collected for some other purpose;
- (2) If the data have been collected from a carefully documented research plot, they can be regarded as precise measurements. If these data are from large production areas, they are nearly always estimates and are subject to sampling error; and
- (3) The problem of specifying the impact of technological change for the historical data and projecting this trend into the future is most troublesome. If not handled properly, the portion of the model related to meteorologically-induced variability will be weakened. (The same problem is also inherent in causal models.)

Most of these yield data series show a comparatively flat trend for the first few decades, with a substantial trend toward higher yield values in the most recent two or three decades. A plausible list of the mechanisms which have caused the recent increases would include: (1) Better seed, (2) more fertilizer, (3) use of insecticides and herbicides, (4) substitution of mechanical energy for animal and human energy, (5) better machinery, and (6) better management. A rational weather-crop yield model theoretically should include these factors as specified variables. Most models do not. Instead, they use "time" or "year" as a surrogate variable.

In a "technology" trend line model, the trend line and meteorological coefficients are estimated concurrently. The model is of the form

$$\hat{Y} - \bar{Y} = f(\text{year}) + g(\text{weather}),$$

where g is evaluated as a non-linear function of deviations from mean weather values.

We are using this kind of technology trend function in operational work in progress at our center in Columbia, Missouri.

Which of the possible specifications of a yield trend function is the right one? We think the one presented above is the most reasonable, but we cannot justify its use in a rigorous manner. Much more work must be done on this important component of yield variability.

Multicollinearity of the "independent" weather variables in the model results in subtle but serious problems in testing hypotheses on the regression coefficients, and in applying the model in a predictive mode. This is a fancy way of saying that there are not many "independent" meteorological variables.

CONCLUDING REMARKS

It is not my intention to discuss in great detail the particular biological, physical, or statistical properties of the large number of models that have appeared in the literature. However, while there must be a proper amount of concern for these matters, the choice of a model should be made on the basis of answers to a very broad question, "For what purpose will the model be used?"

- 1) The model may serve as an investigative tool for better understanding of the complex interactions of the crop with the atmosphere.
- 2) The model may serve as an operational tool to translate the meteorological data from many national weather services into estimates of grain yields as the crop season progresses. The complex system of distributing food grain globally is becoming more, rather than less, sensitive to large scale meteorological anomalies. The use of well-conceived, feasible crop yield-weather models in the management of national and international food grain programs is a comparatively recent phenomenon.

Technical and scientific considerations in the choice of a particular approach to weather-crop yield modeling are important. It is my opinion that we now have completely adequate theoretical and practical knowledge for choosing a modeling approach that will best serve our purposes.

Now, the most difficult remaining problem is to find effective ways to communicate the results of crop-weather model applications to decision makers in government, industry, and international bodies in a credible, useful form.

FOOD PRODUCTION FROM THE OCEANS

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HISTORICAL, PRESENT, AND POTENTIAL HARVEST OF OCEAN FOOD RESOURCES

Historical and Present Production

Over the past decade, considerable controversy has raged about sustainable yields of food resources available in the ocean. Estimates vary to a remarkable degree. This is explainable, in part, by misunderstandings about how estimates were made. Some include only bony fish in their estimates; some include all living plant and animal life in the ocean; others include only that which could be obtained from present harvesting methods; and still others have assumed that new and more highly efficient harvesting gear will be developed. A better perspective on the possibilities of increasing future production can be gained by reviewing past and present production.

The growth in fisheries in the past twenty years has been phenomenal (figure 1). The catch in 1954 was 27.6 million metric tons; a peak of about 70.2 million metric tons was reached in 1971; and a decline in 1972 was due almost solely to the collapse of the Peruvian anchoveta fishery. This was the world's largest fishery, which at the turn of the decade was producing about 12 million metric tons, or 1/5 of the total world catch. In 1973 the anchoveta catch had declined to slightly over 2 million metric tons. The decline probably was due to a combination of overfishing and change in environmental conditions, specifically, the occurrence of the El Niño. The collapse of this fishery vividly points out the need for increased management of fishery resources. This will require much more understanding of the effects of fishing effort and environmental change on resources.

The bulk of the catch over the past several years has been by Peru, Japan, Soviet Union, People's Republic of China, Norway, and the United States, though growth in U.S. fisheries has been stagnant (fig. 2). Much of the growth of Soviet and Japanese fisheries has been due to operation of distant-water fleets. This kind of fishing operation is likely to be increasingly less profitable because of escalating energy costs; and in Japan increased labor costs are now playing a significant role. The growth in Peruvian fisheries was attributed mainly to harvesting of anchoveta by a fleet of some 1300 vessels fishing within a few miles of the Peruvian coast.

Unfortunately, countries that particularly need protein are not the leaders in fish production (table 1). It appears, however, that some countries with unused resources off their shores plan to make a concerted effort to develop them. India has already done so; she has doubled her catch in the past decade.

Figure 1.--World fisheries catch, 1954-73.

WORLD CATCH BY LEADING COUNTRIES

Figure 2.--World fisheries catch by leading countries.

Table 1.--Catch of fish, crustaceans, molluscs, and other aquatic plants and animals, by country, 1973.

Country	Millions of metric tons
Japan	10.7
USSR	8.6
China	7.6
Norway	3.0
United States	2.7
Peru	2.3
India	2.0
Thailand	1.7
Korea, Republic of	1.7
Spain	1.6
Denmark	1.5
South Africa, Republic of	1.3
Indonesia	1.3
Philippines	1.2
Canada	1.2
United Kingdom	1.1

Table 2.--World fish catch by major groups of species.millions of metric tons.*

Group of species	1958	1965	1966	1967	1968	1969	1970	1971	1972	1973
1. Herring, sardine, anchovy, etc.	7.3	16.9	18.7	19.6	20.3	18.0	21.3	19.0	13.5	11.1
2. Cod, hake, and haddock	4.5	6.8	7.3	8.2	9.5	9.8	10.4	10.7	11.5	11.8
3. Miscellaneous marine fishes	5.2	6.4	6.6	7.0	7.4	7.8	8.1	8.6	9.3	9.8
4. Miscellaneous fresh-water fishes	-	-	6.7	7.0	7.0	7.2	7.7	8.2	8.2	8.4
5. Redfish, bass, conger, etc.	2.2	3.2	3.3	3.3	3.3	3.2	3.7	3.8	3.8	3.9
6. Mackerel, snoek, cutlassfish, etc.	1.0	1.5	1.9	2.5	2.9	3.0	3.2	3.3	3.1	3.3
7. Jack, mullet, saury, etc.	1.8	2.2	2.1	2.1	2.0	2.0	2.4	2.9	2.9	3.4
8. Salmon, trout, smelt, etc.	-	0.9	1.2	1.1	1.2	1.4	2.1	2.2	2.5	2.6
9. Tuna, bonito, billfish, etc.	1.0	1.4	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.7
10. Flounder, halibut, sole, etc.	0.8	1.0	1.1	1.2	1.1	1.3	1.3	1.4	1.3	1.2
11. Shad, milkfish, etc.	-	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.7	0.7
12. Shark, ray, chimaera, etc.	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6
13. Shrimp, prawn, etc.	-	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1
14. Oyster	-	0.7	0.8	0.8	0.9	0.8	0.7	0.7	0.8	0.8
15. Clam, cockle, arkshell, etc.	-	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.6	0.6
16. Squid, cuttlefish, octopus, etc.	-	0.9	0.8	1.0	1.2	1.0	0.9	0.9	1.1	1.0

*Data from FAO Yearbook of Fishery Statistics. Catches and Landings, 1968 and 1973.

The herring-, anchovy-, and sardine-like fishes have historically made up the bulk of catch (table 2). In 1973, however, the cod-like fishes surpassed the herring-anchovy-sardine group because of the large decline of the anchoveta catch. Nevertheless, trends clearly suggest that the large increase in fish landings has not been in the expensive delicacies from the sea such as salmon, tuna, and shrimp, but in the cheaper forms of protein such as anchovy.

Potential Production

The above background describes briefly the growth of fisheries over the past two decades and the present status. But what of the future? What is the potential of the ocean to provide much needed food for the world?

Schaefer and Alverson (1968) summarized estimates made by a number of scientists (table 3). These estimates tend to fall into two categories: Prediction based on extrapolation of present trends and success in areas now heavily exploited to like regions of the ocean not yet or only partially exploited; and prediction based on food-chain dynamics, i.e., on the amount of phytoplankton produced naturally in the ocean, and the consequent flow of energy through the food web. Estimates using the latter approach are considerably above those based on the former.

The high estimates (in the 1,000 to 2,000 million metric ton range) do not take into account man's capability to harvest economically, and are more in the realm of theoretical estimates. Thus, they are not indicative of potential yields, especially within the next few decades. When one tempers these estimates with realistic projection of technological and economic capability, those in the range of 80 to 200 million metric tons are more realistic.

More recent estimates made at the FAO Fishery Management and Development Conference, Vancouver, B.C., in 1973 tend to be in this lower range. Moiseev (1973) estimates a total potential catch of fish, large invertebrates, and marine mammals of 90 million tons with the largest increase possible in the Atlantic but the largest percentage increase in the Indian Ocean. This estimate does not include resources such as krill, other zooplankton forms, or seaweed. At the same conference, Suda (1973) suggested a potential marine catch of 93 to 100 million tons. Both these estimates are about twice the current catch, which is approximately 55 million metric tons of the total, ocean and freshwater, of 65 million metric tons.

Two underutilized kinds of marine life, if brought into production, could increase the yield significantly--the harvest of krill in the Antarctic and the harvest of squid ocean wide. Krill is a large shrimp-like crustacean which serves as a major item of the diet of the whales. Some estimates of the sustainable yield of krill range up to 100 million metric tons, but more conservative estimates suggest that an annual yield in the neighborhood of 25 to 50 million metric tons may be possible (Ryther 1969). The USSR is the most aggressive nation so far in attempts to develop krill resources and to process them into an acceptable market item (Fishing News International 1974).

Table 3.--Estimates of total ocean yields of aquatic animals

Author	Forecast	Year estimate made	Method
Thompson	21.6	1949	ext.
FAO	55.5	1955	ext.
Finn	50 to 60	1960	ext.
Graham & Edwards	55 (bony fishes)	1962	ext.
Meseck	55 (by 1970)	1962	ext.
Graham & Edwards	60 (bony fishes)	1962	ext. f.
Schaefer	66 (by 1970)	1965	ext.
Meseck	70 (by 1980)	1962	ext.
Alverson	80	1965	ext.
Bogdanov	70 to 80	1965	ext. f.
Graham & Edwards	115 (bony fishes)	1962	f.
Schaefer	160	1965	ext.
Schaefer	200	1965	f.
Pike & Spilhaus	200	1965	f.
Chapman	1,000	1966	f.
Pike & Spilhaus	180 to 1,400	1962	f.
Chapman	2,000	1965	f.

ext. Extrapolated from catch trends or existing knowledge of world fish resources.

f. Flow of material through food chain.

Present harvest of cephalopod resources (squid, cuttlefish, and octopuses) is about 1 million metric tons. Fishing News International (1973), reporting on the work of Voss, estimates a potential of about 8 to 12 million tons on the shelf and upper slope and an even much higher oceanic potential. Although some view squid with a high degree of revulsion, they are considered a delicacy by many. Furthermore, they are high in protein and may contain more amino acids than fish. Certainly, a major problem in high seas harvesting will be development of efficient harvesting gear.

Another way to increase production is to better utilize the catch already taken. At the FAO products conference in Tokyo, Japan, December 1973, it was pointed out that in world shrimp fisheries alone, about 6 million tons (about 1/10 of total fish catch) of trash fish were discarded for the 1 million tons of shrimp taken annually. The economics of recovery of these discarded fish for useful consumption has prevented their use.

In addition to the loss by discarding trash fish, another high (50%) loss occurs in the processing industry (Finch 1970). This is very high when compared with losses in other animal food processing industries.

Table 4.--Opportunities for increased fish and shellfish production, 1985 and 2000, in millions of tons.

Resource category	Potential increase	
	1985	2000
Conventional species	8	14
Unconventional (krill, squid, etc.)	5	35
Waste elimination (equivalents)	2	15
TOTAL	15	64

The general conclusion of Alverson (1975), in summarizing the various possibilities, is that by 1985 we might increase our marine production by 15 million tons, and by the year 2000 we could be producing 64 million metric tons more than the current 55 million metric tons (table 4).

FISH IN HUMAN NUTRITION

Stillings (1974) points out that animal proteins are higher in quality than proteins of plant origin, in that they contain the balance of amino acids essential to man, while plant proteins usually are deficient in one or more essential amino acids. Unfortunately, however, the distribution of animal protein world wide has long been an overwhelming problem. The ratio of animal protein to total protein for different world areas varies tremendously (table 5).¹

Reporting on the work of Altschul, Stillings (1973) states that diets containing 30 grams per day of protein from animal sources will be adequate regardless of the source of the remainder of the diet; less than 30 grams per day will result in questionable quality and less than 15 grams will result in protein malnutrition. It is obvious from table 5 that a considerable portion of the world's population suffers from protein malnutrition largely because of inadequate distribution systems.

Insofar as world production of animal products is concerned, milk is far greater than any other source. These animal products contribute about 32% of world protein supplies (table 6).¹ Milk contributes about 11%, meat 15%, fish 4%, and eggs 2%. These figures, however, mask the fact that, though meat and milk provide several times as much protein as fish, fish is essential to more people in the world than either milk or meat, largely because of higher use in the immense population in the Far East. Much attention is being paid to fisheries at the present Law of the Sea Conferences because of this fact.

¹Tables 5 and 6 and figure 3 from "World Supplies of Animal Protein" in *Proteins in Human Nutrition*, Academic Press, 1973.

Table 5.--Protein supplies (1963-5) per capita
per day

REGION	POPULATION (1969) * (million)	ANIMAL PROTEIN † (g)	TOTAL PROTEIN (g)
Far East (incl. Main- land China)	1966	8.6	54.8
Near and Middle East	166	14.0	71.6
Africa	297	10.9	58.5
Latin America	276	24.1	67.6
Developing Regions	2705	10.7	57.6
Europe (incl. USSR)	698	42.8	87.6
North America	224	65.3	93.1
Oceania	19	63.9	95.4
Developed regions	941	48.3	89.1
World	3646	21.0	66.1

*FAO (1971a)

†Autret (1970)

Table 6.--Percentage contribution of animal products
to the total protein supply (1963-5)*

REGION	ANIMAL PROTEINS	PROTEIN CONTRIBUTED BY			
		MEAT	EGGS	FISH	MILK
Far East (incl. Main- land China)	15.7	6.6	0.7	4.6	3.8
Near and Middle East	19.6	8.0	0.7	1.4	9.5
Africa	18.6	9.2	0.5	4.1	4.8
Latin America	35.7	18.3	1.9	2.7	12.7
Developing Regions	18.6	8.3	0.9	4.0	5.4
Europe (incl. USSR)	48.5	21.5	3.8	4.2	18.8
North America	69.9	36.3	5.8	2.9	24.9
Oceania	66.9	36.8	4.2	3.1	22.5
Developed Regions	54.2	25.4	4.3	3.9	20.4
World	31.8	14.7	2.1	3.9	10.9

*Autret (1970)

Figure 3.--Percentage increase in world production of animal products.

The percentage growth in world production of animal products shows that fish far surpassed other forms in growth rate from 1950 to 1970 (fig. 3).¹ This tremendous growth is probably one reason why so much has been written about ocean food resources over the past two decades and the development of a mistaken belief that the world could be fed from the oceans if only the ocean resources were developed. This growth, however, has leveled off and, as shown before, actually declined in 1972 and 1973.

In his summary on increasing fish protein supplies, Stilling (1973) remarked:

The utilization of fish protein could be significantly increased by increasing the amount of fish used for direct human consumption and by decreasing the wastage in the fish processing industry. The world supply of fish protein is currently about 3.5 g per caput per day, which includes fish protein converted to animal protein and consumed by man. This value could be increased to about 6.2 g of protein per caput per day if fish used for direct human consumption were increased from 62% (current proportion) to 80% of the total catch and if wastage in the fish processing industry were reduced from 50% to 20%. Taking this one step further, the amount of protein available for human consumption could be increased by an additional 100% or up to about 12 g per caput per day, based on present world population figures, if the total world potential catch of about 140 million metric tons were realized. Unless the problem of pollution of the oceans receives immediate and serious attention, however, the supplies of fish protein for human consumption may fall considerably below the predicted potential.

Schaefer (1968) noted that the oceans are a poor place to look for the total food requirements of the human population but are an excellent source for satisfying the need for animal protein. His rationale for this belief is:

A comparison of the potential harvest of the living resources of the sea at the second trophic level above the plants, with the requirements of 6 billion people, is presented in Table 2-1. The potential harvest is calculated from the net primary productivity, assuming transfer coefficients between trophic levels of 10 and 20%, which almost certainly bracket the true value (Schaefer, 1965). The population requirement assumes a per capita diet of 2500 kcal per day, 80 g per day of total protein, and 15 g per day of animal protein. Although a large part of the present sea-fishery harvest is taken at higher trophic levels, a large and increasing share, currently about 40%, consists of herringlike fishes which feed at the second trophic level, and many of which feed at the first trophic level, above the plants (see Fig. 2-3). At this level, as may be seen from Table 2-1, the total potential yield would be inadequate to satisfy the human caloric requirement for 6 billion people. Besides, there are much better sources on land. With respect to total proteins, the potential yield is easily adequate to satisfy the total human requirement, and for animal proteins the potential yield at this trophic level is between 8 and 34 times

TABLE 2-1

Productivity of the sea in relation to food requirements of 6×10^9 people

	Calories	Total protein	Animal
Population requirement	5.4×10^{18} g-cal/yr	1.8×10^{14} g/yr	3.2×10^{13} g/yr
Total net primary productivity of the sea	1.9×10^{20} g-cal/yr	2.8×10^{16} g/yr	-
Probable potential yield at second trophic level above plants	1.9×10^{18} to 7.6×10^{18} g-cal/yr	2.8×10^{14} to 1.1×10^{15} g/yr	2.8×10^{14} to 1.1×10^{15} g/yr
Portion of need	0.35 to 1.4	1.6 to 6.1	8.7 to 34

the estimated requirement. Thus, even though the full potential yield may not be economically attainable, there is reason to believe that the sea can satisfy all or a large portion of the requirement for animal protein. We will see below that the current harvest of the sea fisheries, about 45 million metric tons per year, may, at a conservative estimate, be increased to 200 million metric tons per year, which, with no wastage, would correspond to the full animal-protein requirement estimated in Table 2-1.

In a more conservative view, Pimentel et al. (1975) note that about 5% of the total protein in the diet of the world's population is now contributed by fish and by the year 2000 (7×10^9 population) only about 4% will come from fish. They view overfishing and energy expenditure in harvesting fish as detrimental to much greater production.

If one assumes that nations of the world are becoming more sophisticated in fishery management, and there is evidence that they are, and that energy demands will subside because coastal fishing fleets will take increasingly more fish than distant water fleets, there appears to be considerable potential for use of fish in supplying needed animal protein. If one uses Alverson's figures for potential catch in the year 2000 (table 4), Stillings' assumptions on fish utilization, and Schaefer's estimate of 80 grams per capita per day total protein and 15 grams of animal protein needed for an adequate diet, and assumes that 20 grams animal protein per capita per day are needed, which is between the estimate of Altschul and Schaefer, over two thirds of the animal protein requirements in the year 2000 could come from fish.

In spite of the potential for use of fish in combating protein malnutrition, little has been done in this regard. In 1975 the Food and Agriculture Organization of the United Nations in cooperation with the Svanøy Foundation and with support from the Norwegian Agency for International Development organized a round table discussion in Svanøy, Norway, on fish utilization and marketing. Potential for increased use of fish products to combat protein malnutrition was pointed out:

An increase in fish consumption could help a great deal to combat and prevent malnutrition in developing countries. It is, therefore, astounding to see the very limited role fishery products play in food aid programmes. Fish is generally not considered in bilateral food aid--the important exception is a programme of the Norwegian Church Relief Agency in Bangladesh which has distributed more than 2,000 tons of fish powder (FPC type B). In the multilateral efforts of the World Food Programme fishery products have represented 3 to 4 percent of the total value of shipments. It is evident that increased contributions of fishery products to food aid are possible. Efforts should be directed at determining the most appropriate products which can easily be incorporated in the diet of aid receiving populations.

CLIMATIC CHANGE AND EFFECTS ON RESOURCES

Over the past several years changes in the ocean environment have caused serious problems in a number of fisheries. In examples of apparent decline in fisheries in relation to a changing ocean environment, caution must be used in interpretation of the data. In some instances the decline may be due primarily to fishing effort too heavy for the fish stock to sustain and not to environmental change, either natural or that caused by pollution. The emerging consensus appears to be, however, that declines in many exploited fishery stocks are caused by a combination of adverse environmental conditions and heavy fishing pressure.

Statistics are not available on what effect climatic change has on total marine production. The best we can do now is point out examples where catastrophic declines in catches may be due to ocean climate change. I will point this out in the Icelandic herring fishery, North Pacific salmon fishery, Peruvian anchoveta fishery, and the U.S. eastern seaboard shrimp fishery.

The combination of heavy fishing and climatic change in the area of the Icelandic herring fishery was catastrophic to the economy of Iceland in the late 1960's. The annual herring catch declined from about 750,000 tons in the mid 60's to about 50,000 tons by 1970. Dickson and Lamb (1971), reporting on the work of Jakobsson, pointed out that migration routes of herring changed (fig. 4) in the 1960's, probably in response to a changing ocean climate. The deterioration of the Icelandic ocean environment in the decade of the 1960's is reflected in the extent of the ice-cover in the late sixties compared with that of earlier years (fig. 5). By the spring of 1968 the southeastward extent of the drift ice north of Iceland was greater than in any year since 1918. This may have been due to a shift in the atmospheric pressure system which suggests strong flow out of the northwest in the decade of the 1960's compared with the previous decade (fig. 6), which would tend to drive the ice pack to more southern latitudes. Furthermore, the ocean currents in the general area of Iceland appeared to change significantly in this period. These events would certainly have some effect on migration routes of the herring, perhaps keeping the stock out of range of the Icelandic fleet. To a country such as Iceland, which depends upon fisheries almost exclusively for its livelihood, events such as this are devastating.

Figure 4.--Summary of recent changes in the feeding migration of herring at Iceland.

ICE EXTENT 8 MAY 1968, SOLID LINE
COMPARED TO NORMAL (1911-1950)
DASHED LINE

ICE SURPLUS
ICE DEFICIT

Figure 5.--Changes in ice cover in the North Atlantic.

Figure 6.--Atmospheric pressure change (mb) in northern latitudes, (1961 to 70) minus (1951 to 60).

A climatic shift which appeared in the Bering Sea in the early 1970's has had a drastic effect on the Alaska salmon fishery and significant effects on other fisheries. The 1974 commercial salmon harvest may have been the lowest since inception of the salmon fishery in the late 1800's and followed almost equal low catches in 1973. The low catches were attributed to the effect of the unusually severe cold years of 1971 and 1972. Ocean sea surface temperatures in the area of the Aleutian Islands were colder in 1971 and 1972 than they had been for at least the previous twenty years (fig. 7). Land stations in Alaska in the winter of 1970-71 reported all-time low temperature readings. The onset in decline of sea and air temperatures appeared to coincide with an unusual southward penetration of the Arctic ice pack (Kukla and Kukla 1974) although as yet it is not known if this was merely a chance relationship, a cause and effect relationship between ice and sea temperature, or a situation in which both events were related to some other environmental variable. McLain and Favorite (1975)² relate the cold sea temperatures to increased northerly winds and large changes in North Pacific atmospheric circulation, which probably would result in southern displacement of the ice pack. The severe environmental stresses may have affected salmon survival in all phases of its life history, i.e., in its life in lakes, streams and

²Anomalous Cold Winters in the Southeastern Bering Sea. Paper presented at the Thirteenth Pacific Science Congress, 18-20 August 1975, Vancouver, B.C.

YEAR

JANFEBMAR

JUL/AUG/SEP

Figure 7.--Sea surface temperatures and anomalies in Marsden Square 197, quarter 1 (in general area of Aleutian Islands) 1948-1974. Solid line is temperature °C; black area is warm anomaly, light shaded is cold anomaly.

Figure 8.--Changes in monthly price of menhaden and soybean meal, 1972-1974.

the ocean, though the severe conditions in the first two habitats appear to be the cause of most mortality.

El Niño off the west coast of South America is an example of a short term climatic shift on the order of 2 years or less. The last major occurrence was in 1972-73; together with excessive fishing pressure, it had a drastic effect on the abundance of anchoveta resources, which in turn had tremendous economic impact throughout the world fish and soybean meal industry (fig. 8). Catch declined from a high of over 12 million tons (about 1/5 of the total world catch of all fish) in 1970 to about 2 million tons in 1973.

One of the strange facts about El Niño is that no one has been able to describe precisely why an El Niño episode occurs. One can say, however, that the phenomenon is characterized by high rainfall and high sea temperatures in coastal areas of Ecuador and northern Peru and the equatorial Pacific Ocean, although there are exceptions to this generality. Coastal temperatures at Puerto Chicama show that fairly strong El Niños occurred in 1925, 1941, 1957, and 1972, and weaker ones in 1930, 1943, 1953, 1965, and 1969 (fig. 9). In late 1974, at an El Niño symposium at the Eastern Pacific Oceanic Conference at Lake Arrowhead, California, Quinn (1974)³ predicted a minor El Niño in

³Monitoring and Predicting El Niño Invasions. Paper presented at 21st Annual Eastern Pacific Oceanic Conference, Oct. 2-4, 1974, L. Arrowhead, Calif.

Figure 9.--Sea surface temperature anomalies, °C,
at Puerto Chicama, Peru 1925-1973

early 1975 based on his studies of variations in atmospheric pressure differences between Darwin and Easter Island which are part of variations in the overall atmospheric circulation commonly called the Southern Oscillation. His prediction appeared to verify, for sea temperatures rose dramatically to the east of the Galapagos Islands in early 1975 but did not reach the Peruvian coast (which may be characteristic of minor El Niños).

The differences in sea surface temperature in the eastern equatorial Pacific between El Niño and non-El Niño years can be striking. In 1972 the November temperature during an El Niño was as much as 10°F warmer than in November of 1973, a non-El Niño year (fig. 10).

These sea surface temperature changes are probably reflected in changes in atmospheric circulation over wide areas of the globe and especially over the North Pacific and the United States. According to Bjerknes (1969) heavy rain in the equatorial region at the time of El Niño is a result of upward transfer of moisture due to ocean temperatures being warmer than the overlying atmosphere which, accompanied by intensive convection, brings moisture to the level of condensation. He further suggests that an anomalous high heat supply in the equatorial Pacific intensifies the Hadley circulation providing more than normal flux of angular momentum to the mid-latitude belt of westerly winds thus affecting the weather over the North American continent. He believes that regular monitoring of sea temperature in the tropical Pacific is indispensable in long-range forecasting for North America. Namias, in his 1972 study and in numerous other studies, also stresses the importance of the oceans in long-range weather predictions.

Studies of this type are increasingly showing teleconnections between the Pacific and Atlantic oceans, thus it may be more than coincidence that the wheat failures in the Soviet Union occurred at the same time as the 1972-73 El Niños.

Quinn (1972) also examined air-sea interactions in the equatorial Pacific and consequent trough and ridge development over the North Pacific and continental United States which appears to affect the eastern seaboard shrimp fishery. This fishery varies much from year to year and appears related to changes in atmospheric circulation. Years of good fishery appear to be related to "warm" years the preceding winter along the eastern seaboard and poor years to "cold" winters (Williams 1969). Johnson and McLain (1975) have identified the two different kinds of atmospheric circulation that predominate in these opposite kinds of years (fig. 11). Poor catches are usually associated with strong trough development at 700 mb in the eastern United States which has a tendency to bring colder continental air masses over the southeastern seaboard and thus colder water temperature (caused by increased evaporation and conduction of sensible heat). Ridge development in the 700-mb circulation over the eastern U.S. has a tendency to block storms of northern origin and consequently air masses of more tropical characteristics predominate; thus the water temperatures remain warmer, a condition more favorable to shrimp abundance.

Though no studies have been made on what effect adverse climatic change may have on total marine production globally, a crude estimate can be made from

Figure 10.--Sea surface temperature anomalies, °F, eastern tropical Pacific Ocean, November 1972 and November 1973

the decline on a few specific species. From the anchoveta decline of about 10.0 million metric tons, off the west coast of South America, one can conclude that a reduction of total world catch in severe cases can be in the order of 15%. This assumes that the reduction is caused by climatic change and not by overfishing, which is tenuous at best. Nonetheless, if adverse conditions struck several of the large fisheries of the world at the same time, a reduction in total world catch of 15% does not seem unreasonable.

Figure 11.--700-mb heights and departures from normal, tens of feet, January 1949 and January 1958. Major departures are enclosed in boxes.

PROBLEMS IN MARINE RESOURCE DEVELOPMENT

Though the potential use of fishery resources as an animal protein source appears to be great, when one reviews problems facing world fisheries he assumes a more conservative view. Problems, in addition to those caused by climatic change, include: (1) The new dimension of the energy crisis will undoubtedly affect high seas distant water fisheries of a number of countries. Steinhart and Steinhart (1974) point out that, from an energy standpoint, distant water fisheries are extremely inefficient. This obviously will give advantage to coastal states, but many coastal states do not yet have the technology to harvest resources off their coasts. In the short run this will be detrimental to fisheries development but could in the long run be beneficial as the coastal states will not expend as much energy in harvesting the resources off their shores and so will be more inclined to manage them properly. (2) The ability of man to maintain favorable marine environment for fishery production in the face of other forms of natural resource development in the oceans and in the face of various types of pollution is not a certainty. (3) Perhaps the most critical immediate problem is the lack of sophisticated management of resources, particularly of stocks fished by a number of nations, which leads to overfishing. The tendency toward overfishing is caused by the absence of sole ownership of the resources. There is no incentive for fishermen to curtail current activities to achieve an optimal time distribution of catches, because no property right guarantees that the fish not taken today will be available in the future. What the fisherman does not catch today simply goes to other fishermen. Fisheries throughout the world have therefore been characterized by a persistent, and in some cases disastrous, tendency toward overexploitation. Recent activities, however, of the International Commission for Northwest Atlantic Fisheries, the International Whaling Commission, the Inter-American Tropical Tuna Commission, and others suggest that many nations are now ready to assume a more progressive attitude in fishery management.

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COMMODITY MODELS AND THEIR USE
IN POLICY ASSESSMENT: THE U.S. SHRIMP MARKET

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INTRODUCTION

Long-term world food prospects have created a new wave of alarm, and recent shortages and high prices of agricultural commodities have rekindled interest in world food supplies. Juxtaposed with the Malthusian concerns with food scarcity is an increasing awareness of our nutritional requirements. The volatility of the food situation requires the continual assessment of policy alternatives. Commodity models have served as an indispensable tool in the assessment of the economic implications of different policies.

A commodity model can be defined as a formal representation of a commodity market, e.g., the fish market. Commodity models are composed of behavioral relationships which reflect the underlying economic, political, and social institutions that exist in a given market.

This paper focuses on presenting a commodity model developed for the U.S. shrimp market, and analyzes the impact of alternative market policies. Section 1 treats some general concerns related to commodity model development. Section 2 is devoted to the presentation of the structure of the shrimp market. The assessment of the impact of different policy opinion is presented in section 3.

COMMODITY MODEL DEVELOPMENT¹

Four major components make up the commodity model approach to policy assessment: Selection of the approach to be taken, selection and specification of the model, model validation and refinement, and application of the model.

In most cases, the policy problem to be solved determines the approach to be taken. Econometric market models, econometric process models, spatial equilibrium models, and activity models provide examples of approaches. The first three methodologies describe the interaction of demand and supply to produce an equilibrium price, transformation of commodity inputs into finished products, and assignment of spatial flows and equilibrium conditions,

¹ Labys (1975, pp. 1-25) was relied upon heavily in developing this section.

respectively. Activity analysis makes it possible to determine the types and levels of various acts that should be carried out to achieve a desired goal.

Model specification and selection is dependent upon the economic nature of market activity. The competitive nature of the market - that is, whether there is a large number of small firms or a small number of large firms - is of importance. The availability and accuracy of market data also affect the specification of the model.

Single equation or simultaneous equation methods can be used to estimate the model, depending upon the method deemed most appropriate. Evaluation of the implications of policy alternatives can be accomplished through the use of multipliers or simulation. Figure 1 is a schematic of the commodity approach to policy assessment.

Market Models

Econometric market models consist of sets of relationships pertaining to the demand and supply for a commodity. Demand and supply relations may be specified for each level in the market chain from primary producers to the final consumers. Further explanatory power can be gained by adding inventory relations when appropriate. Equations (1), (2), and (3) taken together constitute a simple market mode. These are:

$$D = f(P, P_S, Y), \quad (1)$$

$$Q = F(P, N, Z), \text{ and} \quad (2)$$

$$D = Q, \quad (3)$$

where

D = commodity demand,

Q = commodity supply,

P = commodity price,

P_S = prices of substitute commodities,

Y = consumer income,

N = natural factors influencing supply, and

Z = policy variables influencing supply.

Eq (1) states that commodity demand is dependent on price, prices of substitutes, and consumer income. Supply is dependent upon price; natural factors, such as weather; and a policy variable, for example, the number of fishing area closures. Eq (3), the market clearing identity, closes the model. Other possible influencing factors and the stochastic disturbance term have been omitted to simplify the model.

Econometric market models have been employed in a large number of commodity studies. This wide usage is due in part to the fact that the econometric market form of commodity models provides a basis from which process, spacial, and other miscellaneous methodologies follow.

Process Models

Process models are concerned with demand and supply within an industry. It is in this respect that they differ from market models which focus on demand

Figure 1.--Procedure for developing and applying commodity models.

and supply across a market. Prices in market models are determined by the simultaneous interaction of supply and demand. In process models, prices are determined by the level of production and the cost of materials. The production process is the primary concern of process models.

Spatial Models

Spatial equilibrium models have three components. The first is a system of equations describing aggregate demand and supply for each commodity and market. Spatial distribution activities make up the second component. The activities allow product movement when the price differential between two points exceeds the transportation costs. The third component is a set of equilibrium equations. The following system of equations is an example of a spatial model. Let

$$D_i = f(P_i, Z_i), \text{ and} \quad (4)$$

$$Q_i = f(P_i, Z_i) \quad (5)$$

represent the demand and supply for each market. The interregional flow of commodities is obtained by decomposing demand and supply into shipments.

$$D_j = \sum_i X_{ij} \quad j = 1, 2, \dots, n \quad (6)$$

$$Q = \sum_j X_{ij} \quad i = 1, 2, \dots, n \quad (7)$$

The X_{ij} 's in eq (6) and (7) represent the quantities shipped from the i^{th} to the j^{th} region. The equilibrium conditions are given by

$$r_{ij} X_{ij} = 0 \quad \text{for all } i, j \quad (8)$$

where

$$r_{ij} = t_{ij} - (P_j - P_i) \text{ for all } i, j. \quad (9)$$

The variables in eq (4-9) are:

- D_i = commodity demand in region i ,
- Q_i = commodity supply in region j ,
- r_{ij} = net loss or gain in shipping a commodity from region i to region j ,
- X_{ij} = quantity shipped from region i to region j ,
- t_{ij} = transportation costs,
- P_i = price in region i , and
- Z_i = exogenous or policy variables for region i .

The demand and supply components of spatial models are similar to those of market models. However, the equilibrium process is represented through the identification of profits to be realized from the interregional flow of commodities. Profit maximization is assured through the use of linear programming which allows commodities to transfer until demand equals supply in all markets.

Activity Models

The activity approach to commodity models is concerned with normative issues, that is, what activities and level of each should be engaged in to achieve a defined objective. Activity models in general are made up of an objective function and set of constraints. Once the model is formulated, various methods can be employed to obtain solutions.

SHRIMP COMMODITY MODEL

In this section an econometric model of the U.S. shrimp market is presented to illustrate the development of a market form commodity model. Initially, concern is focused on the model specification. Emphasis then shifts to presentation of the statistical results.

Demand and supply relations exist for each level of the marketing chain that channels shrimp from the fishermen to the final consumer. The harvesting, processing, wholesale, and institutional and retail sectors are market levels which perform important functions in delivering shrimp to consumers. Shocks in the marketing system at any one of these levels are capable of altering prices received by fishermen. For example, changes in the cost of services supplied by the retailer will result in price changes at the harvesting level. Thus a model which is complete in the economic sense must include demand and supply equations for each level in the marketing chain. The economic model, once determined, provides a framework making it possible to isolate the impact of changes in selected force.

Figure 2 is a schematic that indicates the various forces determining prices and quantities at each level of the shrimp marketing chain. A symbolic representation of the relationships shown in figure 2 without taking into account the institutional sector, imports, and inventories, follows.

$$F_1 (C, P_r, P_m, Y) = 0; \text{ consumer retail demand} \quad (10)$$

$$F_2 (C, P_r, P_w, M_2) = 0; \text{ retail supply} \quad (11)$$

$$F_3 (W, P_r, P_w, M_2) = 0; \text{ demand of retailers} \quad (12)$$

$$F_4 (W, P_w, P_p, M_1) = 0; \text{ wholesale supply} \quad (13)$$

$$F_5 (O, P_w, P_p, M_1) = 0; \text{ demand of wholesalers} \quad (14)$$

$$F_6 (O, P_L, P_p, M_0) = 0; \text{ processor supply} \quad (15)$$

$$F_7 (L, P_L, P_p, M_0) = 0; \text{ demand of processors, and} \quad (16)$$

$$F_8 (L, P_L, Z) = 0; \text{ harvestor sector supply,} \quad (17)$$

where

C = consumer commodity demand,

Y = consumer income,

P_r = retail price,

P_m = price of meat,

M_2 = cost of retail services,

W = retail commodity demand,

P_w = wholesale price,

P_p = processor price,

M_1 = wholesale marketing costs,

Figure 2.--Selected forces which determine prices and quantities at various levels in the shrimp marketing chain.

O = wholesale commodity demand,
P_L = landing price,
M_O = cost of processing services,
L = landing, and
Z = natural factors.

Market clearing identities exist for each of the market levels.

The realities of data availability make compromises in model construction necessary. Such compromises and simplifications were required to facilitate development of a market model for shrimp. Five relationships make up the structural shrimp system, which was estimated. The first relationship used described the dependence of total shrimp disappearance upon the wholesale price of shrimp. Total disappearance was defined as total supply minus ending stocks, canned pack, frozen exports, and transshipments. Retail price was defined as dependent upon wholesale prices and the cost of marketing services at the retail level. The retail price, the cost of marketing services at the retail level, beginning stocks, total disappearance, domestic landings, imports, and the price of choice beef were determinants of the wholesale price. Forces considered to define ending stocks were total disappearance, beginning stocks, domestic landings, and imports. The wholesale price, domestic landings, and the cost of marketing services at the wholesale level were selected as determinants of the exvessel price.

The simultaneous solution of the five relationships described resulted in numerical solutions for total disappearance, retail price, wholesale price, ending stocks, and the exvessel price, given assigned values to the remaining variables. The cost of marketing services at both the retail and wholesale levels, the price of choice beef, imports, and landings were considered to be determined by forces outside of the structural system. The biological nature of the causes of shrimp abundance served as the justification for handling domestic landings as exogenous. A similar rationale, although not the only one, can be given for treating imports as predetermined.

Structural parameters for the previously defined shrimp model were estimated using monthly data from July 1968 through March 1975. All prices and quantities used were for raw headless shrimp. Prices and quantities were in terms of cents per pound and per 1000 pounds, respectively. In addition, all variables were transformed into logarithms. Statistical results for the five equations estimated are reported in table 1. Most of the variables contained in the equations exhibited signs conforming with economic theory and were statistically significant.

Analysis of Policy Options

Shrimp consumption in the United States has expanded steadily over the past decade and a half. Estimated domestic consumption in 1975 was 421.4 million pounds, as compared to 251.2 million pounds in 1960. This expansion can be attributed to an increase in per capita consumption and to population growth.

Landings by domestic fishermen and imports from foreign countries are the two major shrimp supply sources. Total supply, domestic landings plus imports,

Table 1.--Estimated structural coefficients for monthly shrimp model, July 1968 - March 1975.^{a/}

of shrimp has grown from 267.6 million pounds in 1960 to 438.9 million pounds in 1975.

Since 1950, the composition of the total shrimp supply has undergone modification. Imports were equivalent to about 33 percent of the domestic catch in 1950. Ten years later, in 1960, imports increased to 80 percent of domestic landings and accounted for 45 percent of the total shrimp supply. Imports exceeded domestic landings in 1975 by 23 million pounds and were responsible for 53 percent of total supply.

An indication as to the degree to which expanded consumption has been accommodated by total supply increases can be obtained by considering changes in the retail price of shrimp. Data available indicate that the Baltimore retail price for 31-42 count frozen raw headless shrimp, when adjusted for the changing value of the dollar, increased from \$1.09 to \$1.89 between 1960 and 1975. While these prices are for only one size category, they do serve to indicate that while supply expanded over the 15 year period, it failed to keep pace with demand increases. Deflated wholesale and exvessel prices also exhibited positive trends over the same period. However, the trends were not as strong as that exhibited by retail prices.

While prices at all three market levels (retail, wholesale, and harvest) have been characterized by positive trends, several significant decreases in shrimp prices have occurred since 1960. Severe price drops were experienced in 1963, 1967, 1970, and 1974. The average annual deflated exvessel price decrease in 1974 was the most pronounced, with prices decreasing 38 cents per pound. Also of significance was the behavior of exvessel shrimp prices between 1971 and 1973, just prior to the price drop. During this period, exvessel prices increased by 10.9, 11.4, and 17.9 cents per pound per year, respectively. These three increases represented the largest successive price gains in the 15-year time period between 1960 and 1975.

The severe price drop in 1974 has served as a source of alarm. The continued increase in the importance of shrimp imports has resulted in concern being focused on the impact they have on domestic exvessel prices. Therefore, import reduction will be the policy issue analyzed.

The independent effects of a percentage change in landings, the cost of marketing services at the retail and wholesale levels, and imports appear in table 2.

The short run static or impact multipliers reported in table 1 reflect the influence that a percentage change in an exogenous variable will have upon a jointly determined variable within the same period, while all other predetermined variables remain constant. For example, a 1% increase in the cost of marketing services at the retail level in a given month was indicated to decrease exvessel price by 0.12% in the same month. Of the immediate multipliers derived, the import multiplier was found to be the smallest. Thus, the impact multipliers indicate that current monthly exvessel prices are more responsive to changes in the cost of marketing services, domestic landings, and beef prices than to the quantity of shrimp imported.

Table 2.--Impact, cumulative, and equilibrium multipliers
for the monthly shrimp model.*

Type of Multiplier	Jointly Determined Variable	Exogenous Variables				
		Marketing Cost Retail Level	Domestic Landings	Imports	Price of Choice Beef	Marketing Cost Wholesale Level
Impact	Exvessel	-.1159	-.2983	-.0009	.11855	-.0089
	price					
	Ending	.0000	.1340	.2760	.0000	.0000
	monthly stocks					
One month Cumulative	Exvessel	-.2183	-.4213	-.1202	.3494	-.0100
	price					
	Ending	-.0023	.2940	.5387	.0036	.0011
	monthly stocks					
Two month Cumulative	Exvessel	-.3081	-.5995	-.3384	.4930	-.0115
	price					
	Ending	-.0064	.4439	.7865	.0103	.0022
	monthly stocks					
Three month Cumulative	Exvessel	-.3860	-.8211	-.6379	.6177	-.0132
	price					
	Ending	-.0121	.5832	1.0182	.0194	.0032
	stocks					
Equilibrium	Exvessel	-1.6547	-1.9858	-.2434	2.6480	-.0488
	price					
	Ending	10.8660	12.1868	2.2731	-17.3888	.2819
	monthly stocks					

*The model was estimated using OLSQ techniques. Monthly data from July 1968 through March 1975 were used to obtain parameters of the structural system. All multipliers are reported in percentages.

The cumulative multipliers reflect what will happen to the current and future values of an endogenous variable when the percentage change in the exogenous variable is no longer transient, but is maintained over T time periods. Results reported in table 2 indicate that a sustained 1% increase in the cost of marketing services would decrease the exvessel prices by 0.22% after 1 month. After 2 and 3 months, sustained increases in marketing costs were found to decrease exvessel prices by 0.31 and 0.38% respectively.

Rankings of the cumulative multipliers for the five exogenous variables examined appear in table 3. Domestic landings ranked consistently as the force capable of causing the most pronounced changes in exvessel prices. Next in order of importance was the price of choice beef. The cumulative multiplier effect for beef, while initially strong, tapers off slightly. A resurgence in the ability of beef prices to influence exvessel shrimp prices with the passage of time was indicated by the equilibrium multiplier (column 5, table 3).

The long run static or equilibrium multiplier answers the question as to what the impact of a sustained percentage change in an exogenous variable would be on the jointly determined variables after a long period of time. Imports, which were indicated as producing only slight immediate changes in prices received by fishermen, were characterized by cumulative multipliers which increased in magnitude with the passage of time. In the long run, however, the equilibrium multiplier indicated that the ability of imports to affect exvessel price decreased relative to 4 of the other exogenous variables.

A sustained increase of 1% in marketing cost was found to increase exvessel prices by 0.21% after the passage of one month, 0.31% after the passage of 2 months and 0.38% after 3 months. A continued, indefinite, sustained 1% increase in the cost of retail marketing service was indicated to possess the capability of reducing exvessel shrimp prices by 1.66%. Of the 5 exogenous variables considered, the exvessel price was found to be least responsive to changes in marketing costs at the wholesale level.

Analysis of the role imports play in the determination of domestic exvessel prices resulted in several important findings. First, exvessel shrimp prices were found to be dependent upon a number of exogenous factors. Forces found to affect exvessel prices were marketing costs at both the retail and wholesale level, domestic landings, imports, and the price of beef. From January 1970 through December 1974, the quantity of shrimp imported was characterized by one of the smallest average monthly percentage increases of the exogenous variables examined. Therefore, based on the percentage increases in the exogenous variables over the period from January 1970 and December 1974, and the multipliers reported in table 2, it was concluded that the level of domestic landings, the cost of retail marketing services, and beef prices were more responsible than imports for the 1974 behavior of exvessel shrimp prices.

Conclusion

The volatility of the world food situation demands continual examination of policy alternatives. Commodity models provide useful insights into the economic implications of various policy options. Historically, commodity models

Table 3.--Rankings of cumulative multipliers for selected time periods.

Exogenous Variables	Multipliers Rankings after the Lapse of			
	one month	two months	three months	Na months
Marketing cost Retail level	3	4	4	3
Domestic Landings	1	1	1	1
Imports	4	3	2	4
Price of Choice Beef	2	2	3	2
Marketing cost Wholesale level	5	5	5	5
a. Multipliers listed are equilibrium multipliers.				

have played an important role in the assessment of agricultural policy. It is time that they begin playing a larger role in the assessment of the implications of fishery policy.

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USE OF SOUTHERN OSCILLATION INDICES TO
ASSESS THE PHYSICAL ENVIRONMENT OF
CERTAIN TROPICAL PACIFIC FISHERIES¹

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1. INTRODUCTION

Anomalous equatorial Pacific meteorological and oceanographic conditions and the related occasional El Niño invasions along the west coast of South America are the result of certain large-scale changes in atmospheric and oceanic circulation. These changes appear to be closely associated with variations in the amplitude and period of an irregular interannual fluctuation in the atmospheric circulation called the Southern Oscillation. Time section plots of pressure indices (differences in sea level atmospheric pressure between sites representing the Indonesian equatorial low and sites representing the South Pacific subtropical high) have been used to represent the Southern Oscillation. Also a method using the trends in the monthly mean and 3- and 12-month running mean plots of the index values has been developed for monitoring and predicting significant ocean-atmosphere changes associated with this Oscillation (Quinn, 1974; Quinn and Zopf, 1976).

This paper will provide some background information on this method and how it might be used to assess physical environmental effects in certain tropical Pacific fishery areas. For clarification purposes the following definitions are provided.

The Southern Oscillation (S.O.) was identified as such by Walker (1924). Berlage (1957) loosely defined it as a fluctuation in the intensity of the inter-tropical general atmospheric and hydrospheric circulation over the Indo-Pacific region, the fluctuation to a large extent being dominated by an exchange of air between the South Pacific subtropical high and the Indonesian equatorial low. Troup (1965) defined it as an exchange of air between the Eastern and Western Hemispheres, principally in tropical and subtropical latitudes, and noted that there were various smaller scale displacements of mean pressure systems connected with it. Troup associates this exchange of air with variations in a mean toroidal circulation driven by temperature differences between the two areas (the westernmost equatorial Pacific-Indonesian area; the eastern tropical and subtropical Pacific area). For simplicity Troup (1965) considers there is a single drift of most importance in the upper troposphere and that this flow is from the area of the Indonesian equatorial low across the Pacific to its central and eastern regions. It is

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compensated by a return flow near the surface from the eastern Pacific to the region of the low. There is descent in this circulation over the central and eastern Pacific, ascent in the vicinity of the equatorial low and a toroidal circulation in the vertical-zonal plane is maintained. The pressure changes which result in the index variations discussed in this paper are a consequence of variations in this circulation and related movements of the associated atmospheric centers of action.

The Walker Circulation is considered to be an important part of the mechanism of Walker's Southern Oscillation (Bjerknes, 1969). According to Bjerknes it is a thermal circulation which results from the gradient of sea temperature along the equator. In general air rises over the warm westernmost equatorial Pacific and sinks over the cool eastern and central equatorial Pacific. Hence there is a zonal vertical circulation along the equator with a horizontal pressure gradient westward along the surface and eastward in the upper troposphere. This circulation enters into exchange of absolute angular momentum with adjacent parts of the atmosphere to the north and south (Bjerknes, 1969). The extent of this equatorial Pacific cell and its circulation strength appear in large part to be determined by the extent and intensity of the upwelling of cooler waters to the surface over the eastern, central, and at times part of the western equatorial Pacific, which is also to a great extent determined by the strength of the southeast trades. One might consider it to be the equatorial aspect of the S. O.

The term El Niño-type development is occasionally used for convenience. This broad connotation represents the occurrence of anomalously warm sea surface temperatures in the equatorial Pacific along with abnormally heavy rainfall, and at times a disastrous invasion of anomalously warm surface waters along the coast of Peru (the actual El Niño occurrence). This condition is brought about by relaxation from a prolonged period of strong southeast trades (represented by high S. O. indices). The magnitude of this relaxation and its timing appear to determine whether or not a strong El Niño occurs along the Peruvian coast (Quinn, 1974). The heavy central and western equatorial Pacific precipitation usually starts a few or more months after the El Niño sets in, but this may not always be the case. By using the broader term one avoids getting into arguments over what is and what is not an El Niño and can then account for those events that evolve in a similar manner but vary in timing and intensity.

The anti-El Niño refers to the contrasting situation when 12-month running mean plots of the indices rise steeply for many months and reach and remain at high values. This indicates that a strengthening and strong southeast trade system prevails; therefore, we can expect strong upwelling, anomalously low sea surface temperatures, and abnormally low amounts of rainfall over the equatorial Pacific (Quinn and Burt, 1972; Quinn, 1975), with strong coastal upwelling, low sea surface temperatures, lower sea level, and favorable physical environmental conditions for primary productivity along the coast of Peru.

2. THE INDICES AND THEIR USE

The idea that the S. O. might be particularly useful for the long-range prediction of ocean and weather conditions over the Indo-Pacific region was

discussed by Berlage (1957) and Troup (1965). Although the S. O. is a near-global phenomenon (Berlage, 1966), it is most clearly evidenced over the Indo-Pacific tropics and subtropics. Bjerknes (1969) was particularly interested in the equatorial aspects of the S. O. and found indications of a relationship between the variations in his Walker Circulation and changes in the circulation and weather over the northeast Pacific. All three of these authors recognized the important contribution of the southeast trades (hence, the South Pacific subtropical high) to changes over the equatorial Pacific. However, the extreme lack of data over the southeast Pacific has always drastically limited the effective use of this important center of action (the South Pacific subtropical high).

Several pressure difference indices and their components are now being followed by means of time-section analyses in order to monitor the S. O. and its effects on the southeast trade system. For most of the indices, the Darwin pressure has been used to represent the Indonesian equatorial low component; but pressures from several sites along or near the South Pacific subtropical ridge (Juan Fernandez, Easter, Totegegíe, Rapa, and Tahiti Islands) are being used due to the particular interest in equatorial Pacific changes and the occasional El Niño occurrences. The Darwin component reflects the effects of movements and changes in intensity of the equatorial low, whereas the ridge components indicate changes in location and strength of the subtropical high and the subtropical area most actively affected by the S. O. One index component is also used to reflect those changes in the northeast Pacific subtropical high (located at the former Ship N position, at 30°N, 140°W) which are associated with the S. O. At times, changes in this North Pacific component are significant and imply a larger scale and/or intensity for the development under way. Figures 1 and 2 illustrate the complementary nature of the component inputs to the S. O. indices. They also indicate the complementary nature of the changes taking place in the Indonesian equatorial low and the South Pacific subtropical high as a result of the S. O. Hence, the indices are used to combine the component changes and to represent the S. O. However, when looking into the nature of a development and predicting its future course, it is desirable to study both the indices and the separate component inputs.

Owing to the nature of El Niño and the anomalous equatorial Pacific developments, which may occur once in 2 to 10 years, it appeared most suitable to consider plots of the 12-month running mean values of the components and indices in order to screen out the regular annual cycle and to emphasize the irregular interannual fluctuations (the S.O.). It has been found that these running mean plots of the indices not only represent the variable amplitude and period of the S. O., but they also reflect the stage and intensity of the associated equatorial Pacific developments (Quinn, 1974; Quinn and Zopf, 1976). By being aware of the related developmental sequence leading up to the unusual equatorial conditions, once one determines the existing developmental stage and intensity, he can anticipate conditions that will prevail in a later stage.

Figure 3 shows monthly means as well as 3- and 12-month running means for the Easter-Darwin index for years leading up to two recent strong events (the 1957 and 1972 El Niños). When an event is close at hand, the shorter period means are also studied. The 3-month running means are particularly useful,

Fig. 1. The 12-month running means (points plotted at middle of the 12 months) of sea level atmospheric pressure (mb) for Easter Island and Darwin, Australia for 1949-74.

Fig. 2. The 12-month running means (points plotted at middle of the 12 months) of sea level atmospheric pressure (mb) for Rapa (Austral Is.) and Darwin, Australia for 1951-75.

Fig. 3. Monthly means and 3- and 12-month running means for the difference in sea level atmospheric pressure (mb) between Easter Island and Darwin, Australia for 1953-57 and 1969-72.

since they retain the regular annual cycle (with its peak near the beginning of the year and its trough near the middle) as well as the irregular inter-annual fluctuation. When the two fluctuations are out of phase they counter-act one another, and the so affected annual peaks and troughs become stunted. Equatorial extremes in sea surface temperature and rainfall appear to be closely associated with situations where the annual fluctuation and S. O. are in phase or nearly so. In such cases, indices make a large excursion from the high peak of a strong southeast trade situation near the beginning of a year to the deep trough and weak southeast trade condition near the middle of the following year. When the troughs of the fluctuations are out of phase the resulting trough is shallow and the event weak. If the pre-event peak rises sharply from an earlier trough, it indicates the S. O. period is shortening and we can get a rough estimate of its period by doubling the time it took to rise to the peak. The ideal circumstance for a strong El Niño occurrence is to have a pre-event peak >13 mb (for the 12-month running mean of the Easter-Darwin index) near the beginning of a year and an in-phase trough near the middle of the following year, as happened in the case of the unusual 1972 El Niño.

Figure 4 shows how closely the western equatorial Pacific rainfall trend (as represented by Tarawa) relates to the Rapa-Darwin index. Although Tarawa rainfall data are used here, Quinn and Burt (1970, 1972) show that for the most part the large equatorial rainfall variations are related for equatorial Pacific stations between 155°W and 165°E . In figure 5 the periods of heavy equatorial rainfall and El Niño occurrences are shown in relation to the 12-month running mean plot of the Easter-Darwin index.

Figure 6 shows how the 12-month running mean plot of the Easter-Darwin index relates to the 12-month running mean plots of zonal wind components at 850 mb and 150 mb over Canton Island. It shows that when the index is high the easterly component is strong at 850 mb and the westerly component is strong at 150 mb; and when the index is low the easterly component is weak at 850 mb (individual monthly values show reversals in direction when deep index troughs occur) and the westerly component is weak or reverses direction at 150 mb. These zonal wind fluctuations are a result of the variable zonal vertical circulation of the Pacific Walker cell as it shifts in location and intensity. The resulting variations in strength of these zonal wind components at the surface (represented by 850 mb components here) significantly affect the equatorial oceanic circulation and sea surface temperatures.

It appears that the Easter-Darwin index and Easter component plots are generally most useful both for monitoring what is occurring and for anticipating what will occur in the eastern equatorial Pacific and along the west coast of South America. (At times, the Juan Fernandez-Darwin index is also of great value for these purposes.) For activity in the western equatorial Pacific, a study of the other indices and consideration of both components is also recommended.

It also appeared that this monitoring and prediction technique could be applied to the anti-El Nino type condition (where a strong southeast trade system, strong equatorial upwelling, low sea surface temperatures, and anomalously small amounts of rainfall occur over the equatorial Pacific, as well

Fig. 4. Comparison of 12-month running means (points plotted at middle of the 12 months) of rainfall (mm) for Tarawa (Gilbert Is.) to 12-month running means of difference in sea level atmospheric pressure (mb) between Rapa (Austral Is.) and Darwin for 1951-75.

Fig. 5. The 12-month running means (points plotted at middle of the 12 months) of difference in sea level atmospheric pressure (mb) between Easter Island and Darwin, Australia for 1949-74. Periods of El Niño and abnormally heavy central and western equatorial Pacific rainfall are indicated.

Fig. 6. The 12-month running means of the difference in sea level atmospheric pressure (mb) between Easter Island and Darwin, Australia are compared to 12-month running means of the zonal wind components (m/sec) at the 850 mb and 150 mb levels over Canton Island.

as strong coastal upwelling and below normal sea surface temperatures off the west coast of South America) (Quinn, 1975). In Quinn and Burt (1972) it was noted that persistently high Easter-Darwin pressure differences favored the extensive unusually dry equatorial Pacific conditions and several examples were cited where this opposite extreme prevailed over periods 18 months to 3 years in length. In this case, one must again follow the trends in the indices to determine what is taking place; and when the 12-month running mean plot rises steeply for many months and reaches and remains at high values, it indicates that a strengthening and strong southeast trade system prevails and that widespread upwelling and anomalously low sea temperatures have returned to the equatorial Pacific and the coastal region of western South America. The height and breadth of the 12-month running mean peaks determine the degree and time span of developments which favor this widespread upwelling condition. Persistence-type outlooks might be more appropriate for developments of this nature, since we will often be dealing with peaks of lesser intensity than the pre-El Niño variety and also since such activity may often persist for periods ranging 1 to 3 years. The 12-month running means of the S. O. indices and monthly sea surface temperature analyses (U.S. Department of Commerce, 1972-76) are excellent tools for monitoring such developments and issuing persistence-type outlooks. An approaching deep 12-month running mean trough will signal the end to conditions of this nature.

3. STATISTICAL FINDINGS

Figures 7 and 8 show the general consistency between index trends, and figures 1 and 2 show the complementary nature of component trends that cause the index features. Correlation coefficients between the index components at various lags are shown in table 1 and reveal the high degree of correlation between the complementary changes taking place in the components. The highest negative correlations occur when the equatorial low component (Darwin) lags subtropical high components (Juan Fernandez, Easter, Totegegíe and Rapa) of the indices by 2 to 5 months. Changes in the Rapa component generally show up farther in advance (5 months) of the complementary Darwin changes than do the other ridge component changes (2 to 4 months).

Tables 2, 3, 4, and 5 show the correlation coefficients at a number of lags between the indices and rainfall for several island sites in the equatorial Pacific (Tarawa at 1°21'N, 172°56'E; Washington at 4°43'N, 160°25'W; Ocean at 0°52'S, 169°35'E; Fanning at 3°55'N, 159°23'W); and the high degrees of correlation are readily apparent. In general, the highest negative correlations are noted when the rainfall lags behind the pressure values. The changes in the Rapa index show the greatest lead time over rainfall changes, and generally lead rainfall by 3 to 4 months at the 4 stations studied here.

4. DISCUSSION

This time-section analytical approach, as applied to the S. O. indices and their components, appears to be highly effective for monitoring the nature and intensity of the anti-El Niño and El Niño-type developments; and tests so far indicate it can also be used quite effectively for foreshadowing such changes 1 to 8 months in advance. Its use was predicated on the exceptionally

Fig. 7. The 12-month running means (points plotted at middle of the 12 months) for difference in sea level atmospheric pressure (mb) between Juan Fernandez I. and Darwin, Australia (JF-D), between Easter I. and Darwin (E-D), between Totegegrie (Gambier Is.) and Darwin (T-D), and between Rapa (Austral Is.) and Darwin (R-D) for 1949-60.

Fig. 8. The 12-month running means (points plotted at middle of the 12 months) for difference in sea level atmospheric pressure (mb) between Juan Fernandez I. and Darwin, Australia (JF-D), between Easter I. and Darwin (E-D), between Totegegie (Gambier Is.) and Darwin (T-D), and between Rapa (Austral Is.) and Darwin (R-D) for 1961-75.

poor synoptic surface data coverage over the eastern equatorial and southeast Pacific; and it seems to be particularly suited to coping with this severe data limitation since the 12-month running means of the indices and their components bring out quite clearly the more subtle long-term trends that are associated with large-scale changes in the southeast trade strength and its effects on equatorial Pacific meteorological and oceanographic conditions.

In the prediction of El Niño-type activity the method can be most effectively applied to the nature of the initial event following relaxation from a high 12-month running mean peak rather than to the occurrence or recurrence of a later event where running means of the index remain low or return to a low value after a short excursion upward into a smaller secondary peak (Quinn and Zopf, 1976). In cases of the latter type, outlooks must be of a much shorter duration, the alternative being a more speculative long-range outlook which must reach beyond the indications of the existing trend and depend heavily on a projected S. O. trend and experience gained from case-history studies of analogous developments. (In general, the time involved in relaxation from the high pre-event peak to the projected trough determines how far in advance of event occurrence a fairly firm outlook can be given.)

This method can add much to the value of the routinely prepared synoptic analyses over this data-poor region [e.g., synoptic weather analyses (which have a generally poor and highly variable coverage over this region), sea surface temperature analyses and satellite cloud cover photos] by providing developmental continuity and an indication of the direction and magnitude of the long-term changes taking place over this region.

5. USE OF INDICES TO ASSESS THE PHYSICAL ENVIRONMENT OF CERTAIN TROPICAL PACIFIC FISHERIES

It would appear that this monitoring and prediction method could be applied in the assessment of favorable or unfavorable physical environmental changes which may act directly or indirectly on certain tropical Pacific fisheries. One would be particularly concerned with the type, magnitude, and persistence of such changes. For instance, from a scan of the indices in figures 7 and 8, one would in general expect a strong southeast trade system, strong south equatorial current, strong equatorial upwelling, low equatorial sea surface temperatures, a weak equatorial counter current, and widespread, strong upwelling and low sea surface temperatures off the Peruvian coast during the following periods: 1950, 1954-56, 1962-early 1963, 1964, late 1966 to early 1968, 1970-71, and late 1973-74. These periods would be expected to show relatively high primary productivity in the equatorial and coastal upwelling zones. Likewise, one would expect to see a weak southeast trade system, weak south equatorial current, a slackening or cessation in equatorial upwelling, high equatorial sea surface temperatures, a strong equatorial counter current and the rest of the El Niño type conditions during the following periods: latter half of 1951, 1953, 1957-58, late 1963, 1965 to early 1966, 1969, and 1972 to early 1973. These periods would be expected to show relatively low primary productivity in the involved equatorial and coastal zones. Further study by fishery biologists would be required to complete the fishery assessment, since they must take into account such things as the severity of an El

Niño, the rate of recuperation in a fishery, the effects on different types of fisheries (e.g., tuna, anchoveta), etc.

Also, as indicated in the earlier discussions on use of the indices and components in monitoring and predicting anti-El Niño and El Niño-type activity in the equatorial Pacific and along the west coast of South America, one should not rely entirely on the guidance from a single index plot for assessing the physical environmental factor of involved fishery areas but should also consider: (1) the best indices to use in assessing the particular fishery of interest; (2) the separate index components, since there is a very close relationship between the strength of the southeast trades and the ridge component values (and cases arise where an unusually low Darwin input may falsely infer a high Easter component); (3) the trend of the S. O., considering its current and projected phase relations with the regular annual fluctuation.

6. THE FUTURE

Up through the first half of this century the only El Niño events that we heard much about were those that occurred in the 1891, 1925-26, and 1939-41 periods, and here the principal problems were violent weather, flood destruction, and enormous sea life destruction. It is expected that an event such as occurred in 1965 would have gone unheralded if it had occurred several decades earlier. However, over the past 20 to 25 years the Peruvian economy and world food and fertilizer demands have grown increasingly dependent on the Peruvian anchoveta fishery, and much more attention has been focused on El Niño occurrences due to their critical effects on this fishery. Hence, events of a similar nature but lesser intensity have now become of greater concern to us.

Considering figure 4 and its indications that the larger rainfall peaks are associated with the stronger El Niño-type developments, earlier rainfall records for Malden ($4^{\circ} 02'S$, $155^{\circ} 00'W$), Nauru ($0^{\circ} 30'S$, $167^{\circ} 00'E$), Ocean and Fanning Islands would indicate that El Niño-type events which could have significantly affected the anchoveta fishery may also have been associated with the following additional heavy equatorial Pacific rainfall periods that occurred during the early part of this century: 1899-1900, 1902, 1905, 1911-12, 1914-15, 1918-19, and 1930.

In the future, ocean-atmosphere fluctuations of the type discussed in this paper, which affect anchoveta, tuna, and perhaps other fisheries over the lower latitudes of the Pacific, are likely to become more crucial to us as we depend more and more on optimal utilization of all available food resources; hence, the weaker El Niño-type events will become of more concern to us as they take their toll on fishery output. For instance, a small event following a large one may delay fishery recuperation; and, if several such disturbances occur over a 5- to 10-year period, the cumulative effect on the fishery may reach disastrous proportions.

Table 1. Lag correlation coefficients between pressure at ridge sites (Juan Fernandez, Easter, Totegegíe, Rapa) and Darwin (considering 12-month running means).

<u>Lag in Months</u>	<u>Juan Fernandez and Darwin</u>	<u>Easter and Darwin</u>	<u>Totegegíe and Darwin</u>	<u>Rapa and Darwin</u>
-1 (Darwin ahead of ridge site)	-.463	-.593	-.613	-.495
0 (no lag)	-.478	-.653	-.656	-.586
1 (ridge site ahead of Darwin)	-.494	-.703	-.686	-.663
2	-.504	-.741	-.701	-.730
3	-.508	-.758	-.699	-.778
4	-.504	-.759	-.682	-.809
5	-.493	-.744	-.652	-.825
6	-.473	-.713	-.604	-.819
7				-.795
Period of record	1911-75	1948-75	1952-75	1951-75

Table 2. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegie-Darwin, Rapa-Darwin) and Tarawa rainfall (considering 12-month running means).

Lag in Months	JF-D Index and Tarawa Rainfall	E-D Index and Tarawa Rainfall	T-D Index and Tarawa Rainfall	R-D Index and Tarawa Rainfall
-1 (rain ahead of pressure)	-.664	-.682	-.675	-.550
0 (no lag)	-.702	-.731	-.722	-.619
1 (pressure ahead of rain)	-.722	-.765	-.752	-.676
2	-.723	-.780	-.762	-.714
3	-.707	-.776	-.751	-.733
4	-.674	-.754	-.720	-.732
5	-.626		-.670	
6	-.566	-.655	-.605	-.677
Period of record	1948-75	1948-75	1952-75	1951-75

Table 3. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegíe-Darwin, Rapa-Darwin) and Washington Island rainfall (considering 12-month running means).

Lag in Months	JF-D Index and Wash. Rainfall	E-D Index and Wash. Rainfall	T-D Index and Wash. Rainfall	R-D Index and Wash. Rainfall
-1 (rain ahead of pressure)	-.627	-.663	-.671	-.601
0 (no lag)	-.651	-.708	-.714	-.667
1 (pressure ahead of rain)	-.660	-.740	-.742	-.725
2	-.655	-.754	-.752	-.764
3	-.631	-.751	-.741	-.784
4	-.593	-.733	-.713	-.783
5	-.545		-.673	-.771
6	-.504	-.658	-.618	-.739
Period of record	1946-73	1948-73	1952-73	1951-73

Table 4. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegíe-Darwin, Rapa-Darwin) and Ocean Island rainfall considering 12-month running means.

Lag in Months	JF-D Index and Ocean Rainfall	E-D Index and Ocean Rainfall	T-D Index and Ocean Rainfall	R-D Index and Ocean Rainfall
-3	-.713	-.621		-.574
-2			-.773	
-1 (rain ahead of pressure)	-.752	-.706	-.804	-.696
0 (no lag)	-.756	-.732	-.823	-.744
1 (pressure ahead of rain)	-.749	-.744	-.825	-.775
2	-.733	-.743	-.811	-.794
3	-.707	-.727	-.781	-.798
4				-.789
6	-.568	-.599	-.608	-.727
Period of record	1911-70	1948-70	1952-70	1951-70

Table 5. Lag correlation coefficients between pressure indices (Juan Fernandez-Darwin, Easter-Darwin, Totegegíe-Darwin, Rapa-Darwin) and Fanning Island rainfall considering 12-month running means.

<u>Lag in Months</u>	<u>Jf-D Index and Fanning Rainfall</u>	<u>E-D Index and Fanning Rainfall</u>	<u>T-D Index and Fanning Rainfall</u>	<u>R-D Index and Fanning Rainfall</u>
-2	-.556	-.603	-.634	-.501
-1 (rain ahead of pressure)	-.585	-.658	-.690	-.574
0 (no lag)	-.602	-.704	-.730	-.639
1 (pressure ahead of rain)	-.606	-.734	-.755	-.691
2	-.595	-.747	-.762	-.727
3	-.570	-.743	-.749	-.749
4	-.536	-.726	-.721	-.756
5	-.491	-.695	-.680	-.750
6	-.436	-.651	-.624	-.726
Period of record	1922-73	1948-73	1952-73	1951-73

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TROPHODYNAMICS AND HARVESTED FOOD WEBS

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LIMITING FACTORS IN MARINE AND TERRESTRIAL ECOSYSTEMS

Marine and terrestrial ecosystems respond to most of the same physical and chemical forcing functions: nutrients, light, and temperature. They differ in their requirement for water and the degree to which they can be manipulated and harvested. Intensive cultivation is not possible in most marine systems on the scale currently practiced on land. Western agriculture is characterized by genetic manipulation, intensive application of nutrients, concentration of biomass, reduction of disease and parasites by artificial means, and the imposition of short food chains (usually two trophic levels). Marine food chains leading to harvestable products are manipulated primarily by the removal of adults and are characterized by longer food chains (three to five levels). The end result is that marine systems yield organic matter with lower efficiency and with more dependence on climate rather than weather.

MARINE PRODUCTION SYSTEMS

It is possible to distinguish among several different types of production systems, each with unique characteristics. These systems, or their end products, include coastal aquaculture bearing some resemblance to agriculture in being energy and nutrient intensive and producing upper trophic level organisms; coastal plankton-feeding fish; coastal demersal carnivorous fish; and pelagic carnivorous fish.

The natural distribution and productivity of these systems is dependent upon ocean circulation only. Circulation patterns advect nutrients, carry eggs and larvae into or out of suitable areas for settlement, growth, or development, or transport the adults. Equally high production at high or low latitudes in regions of intense circulation suggest that light is not ultimately limiting.

The amount of production at any given trophic level is approximately 80% less than at the preceding trophic level. This difference is attributable largely to respiratory losses but includes mortality by other than predation. It follows that, with a large loss at each trophic level, a point will be reached at which not enough energy and mass is passed on to sustain a self-reproducing population. The maximum possible number of levels appears to be five (or six if decomposers are included). It also follows that the greatest biomass usually exists at the lower trophic level. However the lowest trophic levels

in the oceans (phytoplankton and zooplankton) are so dilute and variable in composition, they are not economically harvestable. The lowest trophic levels with organisms sufficiently large to be catchable economically are shrimp, coastal plankton-feeding fish, and baleen whales. The highest trophic-level fish (tuna, salmon) constitute luxury foods on the world market and harvesting them exclusively is not a very efficient use of marine production. A fishery management strategy that proposes to harvest large quantities of low trophic level organisms involves certain trade-offs, however. For example, baleen whales around Antarctica have been reduced to very low levels. It is now proposed to either harvest the food of the whales (krill) directly or to introduce a new predator (salmon). Either strategy could prevent the recovery of whale stocks or drive them closer to extinction by reducing their food supply.

PREDICTIVE MODELS

Predictive numerical models enable us to better understand complicated ecological relationships. At the present state of knowledge, most models are not predictive in a useful sense because data are inadequate and the phenomena of interest are frequently large step functions. Understanding the qualitative interrelationships must precede precise quantification of those relationships and may be entirely adequate for management purposes. Some general cases may be examined.

Coastal plankton-feeders tend to have unstable populations particularly when overfished. They are short-lived, very fecund, and each year-class is at the mercy of current systems that carry the eggs on or off shore. One bad year may be followed by a good year. Heavy overfishing combined with poor conditions for larval survival in a given year can lead to a rapid population collapse, as seen in the North American menhaden fishery or the Peruvian anchovy fishery.

Demersal carnivores tend to have stable populations since the individuals are long-lived. Successful year classes are the exception rather than the rule. A successful year class can sustain a fishery, if not pushed too hard, for several years. Abundant food or a favorable circulation pattern, in any one year, are not as important for demersal carnivores as they are for plankton feeders. Continuous overfishing on demersal fish has depleted these stocks in many parts of the world. Increasing emphasis on industrial fisheries for plankton feeders coupled with unfavorable years for larval development or circulation failures has led to catastrophic declines.

ECOLOGICAL CONCEPTUAL MODELS FOR FISHERIES MANAGEMENT

There are four basic approaches to the management of what are essentially wild stocks, ranging from the simplest approach, the species of interest, to the most complex, the whole system. The simplest approach is to examine the population dynamics of the species of interest in isolation from ecological relationships or environmental influences. This approach is successful in determining the influence of fishing pressure over a period of time but does not provide predictions of successful year classes or catastrophic collapse.

Prey-predator and competition models are next in complexity but are seldom used in fishery management. Prey-predator models are useful when the predator feeds on only one or two species whose dynamics are equally well known. These models help to account for cyclic trends in populations. Competition models are similar to prey-predator models and could have great utility in fisheries management. For example, one could manage for species diversity and productivity by selective harvesting of less valuable but competitive species. Implicit in this approach is the use of all harvested organic matter to avoid waste.

Finally, environmental models, while of greater complexity than population models, appear to be most successful in predicting fluctuations in stocks. This approach requires some population dynamics data (man is the predator in this case and changes the age composition of the stock by selective harvesting), and includes an analysis of environmental factors that transport eggs, larvae and adults, or affect the availability of food to larvae at critical times. The environmental factors most important are those that affect general circulation patterns, geostrophic flow, and upwelling. Since these factors vary on a climatological time scale it should be possible to estimate reproductive success in advance and tailor fishing strategies accordingly.

A GLOBAL OCEAN-ATMOSPHERE CLIMATE MODEL

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SUMMARY OF PRESENTATION

A joint ocean-atmosphere model covering the entire globe has been constructed at the Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA. Our goal is to simulate the basic features of the climate in order to identify the effects of ocean currents in maintaining the climate. There is little doubt that the interaction between the ocean and the atmosphere is one of the most important processes which control the climate. For example, the atmosphere exerts wind stress upon the ocean surface and drives the ocean currents. On the other hand, the oceans supply water vapor to the atmosphere and control the hydrological cycle. The oceans also transport and store large amounts of heat and thus reduce the latitudinal gradient of temperature and the amplitude of seasonal variation of temperature in the atmosphere. Since the oceans are so closely coupled to the atmosphere, any change in climate usually is related to a change in sea surface temperature, and vice versa. Thus, it is necessary to include the effects of ocean-atmosphere coupling into numerical models. in view of the strong control of the oceans upon the climate.

Using the joint model, one can perform various controlled numerical experiments. Some of the major objectives of these experiments are to: 1) determine the similarity of the model to the actual atmosphere-ocean system; 2) improve our understanding of the climate; 3) investigate the change of climate due to man's activities. It is desirable to understand how climate is determined before attempting to evaluate the possibility of climate change.

Several years ago, Bryan and Manabe (Bryan, 1969; Manabe, 1969) at GFDL constructed a joint ocean-atmosphere model which had idealized topography and a domain covering one-third of the globe. The model had many simplifications, yet their study seems to demonstrate the feasibility of obtaining a quasi-equilibrium climate¹ with many realistic features. Encouraged by these early results, we decided to construct a joint model with global domain and realistic topography, having a computational resolution of 500-km grid spacing. The details of the results obtained from the integration of the global ocean-atmosphere model are discussed by Bryan et al. (1975) and by Manabe et al. (1975). The results show that the joint model simulates some of the basic features of the climate. However, the coarse computational resolution does

¹Here, quasi-equilibrium climate means a quasi-steady state of the model atmosphere and ocean in which the variables fluctuate around certain constant values.

not allow ocean and atmosphere circulations to reach their full intensity. As Holloway and Manabe (1971) have shown, the results from the GFDL atmospheric models improve significantly when the grid size is reduced from 500 to 250 km. At present we are testing a joint model in which the grid spacing is 250 km in the atmospheric part of the model and 500 km in the oceanic part. An example of the joint model simulation is presented in Figure 1, which shows the distribution of surface temperature. The figure shows that the model is capable of simulating the major western boundary currents and equatorial upwelling. However, their intensity is, in general, too weak. The coarse computational grid resolution in the oceanic part of the model requires the use of a very large subgrid-scale viscosity to obtain results that are free of modes induced by the computational scheme. This may be partly responsible for the failure of the model to reproduce the observed features quantitatively.

In the joint model described here, the annual mean distribution of solar insolation is prescribed. The ocean part of the joint model predicts an excessive buildup of sea ice in the Arctic Ocean. This is partly due to the lack of seasonal variations in the model which does not allow the extremes of summer warming that are actually observed at higher latitudes. A joint model with seasonal variation is now being tested.

One of the main objectives of our present studies is to test the preliminary version of the joint ocean-atmosphere model. In view of the deficiencies of the version described here, the results obtained should be regarded as tentative. It is encouraging however that the model climate resembles the actual climate in many respects.

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Figure 1.--Surface temperature distribution from the annual mean ocean-atmosphere model.

U.S. LIVING MARINE RESOURCES:
A MODEL TO ESTIMATE THE UPPER
LIMIT OF PRODUCTION

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ABSTRACT. An exponential model, based on the concept of a "food chain" but with the flow of biomass considered as a continuous rather than a stepped function, was used to estimate the upper limit of harvestable production of living marine resources from waters off the U.S. coasts. The present removals from these waters total just over 8 million metric tonnes. The upper limit of harvestable production is estimated at about 13 (range: 9 to 19) million metric tons.

INTRODUCTION

The marine ecosystem is a complexity of entangled food webs and dynamic interactions. The upper limits of biomass production available to man can be estimated by considering the flow of biomass through a food chain of discrete trophic steps. Ryther (1969) analyzed world "fish" production by this method. He partitioned the world oceans into three regimes each with a particular food chain. In each regime the biomass is taken to flow from one trophic step to the next with a certain efficiency. The efficiency is defined as the ratio of biomass produced at one step to the biomass produced at the next lower step in the food chain. The food chain model then gives an equation: $P = B \times E^n$, where P is the production at the nth trophic step, B is the primary biomass produced by photosynthesis, and E is the efficiency of transfer from one trophic step to the next.

I propose a model in which the flow of biomass is considered a continuous exponential function rather than a stepped power function. Because the marine ecosystem "food chain" is actually a complex "food web" and the biomass produced in any "trophic interval" is obtained from several "trophic intervals," it is appropriate to consider trophic position as any of an infinite number of points on a trophic continuum. An important concept of the model is that total input must equal total output, when averaged over an appropriate time interval.

The "food chain" equation relates only primary biomass production to "fish" production. The efficiency of transfer, raised to the power of the trophic position, represents the ratio of the biomass produced to the sum of biomass produced plus biomass lost from the system through natural processes such as metabolism.

To apply the model to any given region, inputs and outputs of biomass other than primary production and man's removals must be considered. These inputs/outputs include, but are probably not limited to:

- a. Advection of primary biomass into or out of the region;
- b. advection of detrital biomass into or out of the region;
- c. migration of biomass;
- d. discard of "fish" parts, such as eviscera, as detrital biomass; and
- e. discard of by-catch as detrital biomass.

THE MODEL

Start with the equation for the food chain model:

$$P = BE^n, \quad (1)$$

where P is the production at the trophic position n, B is the primary biomass produced by photosynthesis, and E is the transfer efficiency through the trophic continuum. Because n can be a non-integer value, transform the equation to a log equation:

$$P = B \text{ antilog } (n \log E). \quad (2)$$

Recognizing that efficiency may not be a constant along the trophic continuum, I used an integral expression to obtain an average efficiency:

$$P = B \text{ antilog } ((n+1/n) \int_0^n \log E \, dn) = B \text{ antilog } (\int_0^n \log E(n) \, dn), \quad (3)$$

where the term E(n) in the last form indicates that the efficiency is a function of the trophic position. This integral expression can be easily evaluated in three simple cases in which efficiency is a constant, a step function, or a linear function of trophic position.

I used the second case, with efficiency one value for the first "trophic step" and another value for all higher trophic positions, that is: $E = E_0$ for $0 < n \leq 1$, $E = E_n$ for $n > 1$. The model equation then becomes:

$$P = BE_0 \text{ antilog } ((n-1) \log E_n). \quad (4)$$

I used 0.20 for E_0 and 0.15 for E_n . These values were determined to be reasonable by Parsons and Takahashi (1973, p. 124).

Next consider what fraction of the potential production is available to man. Ryther (1969) used a ratio of 0.5, based on estimates from one fishery. In the absence of a better estimate, I used 0.5, and the model became:

$$P = 0.5 BE_0 \text{ antilog } ((n-1) \log E_n) = 0.5 \times 0.2B \text{ antilog } (-0.82391(n-1)). \quad (5)$$

Now consider inputs and outputs of biomass not accounted for by the above equation. The simplest method is to use the biomass and the trophic position of each component of other inputs/outputs and to make corrections to B using the inverse expression of the model equation, without the availability ratio:

$$\Delta B = \Delta P / (E_0 \text{ antilog } ((n'-1) \log E_n)) = \Delta P / (0.2 \text{ antilog } (-0.82391(n'-1))) \quad (6)$$

where ΔB is the correction to be applied to B, ΔP is the biomass of the particular input/output component, and n' is the trophic position of the particular input/output component.

DATA

To apply the model to the U.S. living marine resources, one needs to define:

1. Regions to which we apply the model;
2. time interval;
3. primary biomass produced by photosynthesis;
4. trophic position at which we remove production; and
5. other inputs/outputs and their trophic positions.

Regions

This model was applied to the waters extending from the U.S. coast to the limits of the continental shelf or to the 200-mile limit. The total area, 2.06 million square kilometers, was divided into five regions:

North Atlantic - from Maine to Virginia, out to the limits of the continental shelf;

South Atlantic - from North Carolina to the Florida Keys, out to 200 miles;

Gulf of Mexico - out to the limits of the continental shelf;

California - out to 200 miles; and

Pacific Northwest - Oregon, Washington, Gulf of Alaska, and east Bering Sea, out to the limits of the continental shelf.

Time Interval

The time interval was taken as one year. While there are differences in primary biomass production from year to year, their effects are somewhat

smoothed by the integrating nature of the ecosystem. The effect of fluctuations in primary biomass production would be most noticeable in short-lived species with a low trophic position.

Primary Biomass

The primary biomass produced by photosynthesis in each region was calculated by multiplying the primary carbon fixed by 20.0. This ratio of primary carbon was calculated from data in Parsons and Takahashi (1973, table 12, p. 49). The amount of primary carbon fixed by photosynthesis was estimated from data presented by Moiseev (1971, table 38, p. 103 for average annual photosynthetic rates; table 16 and 18, pp. 27 and 29 for shelf areas). Moiseev presented average annual photosynthetic rate by water type, obtained from a reanalysis of data presented by Koblents-Mishke, Volkovinskii, and Kabanova (1968).

The total primary biomass produced annually in the area of consideration is about 4,400 BU (Biomass Units = 10^6 metric tonnes per year). The production by region ranged from 466 BU in California to 1,900 BU in the Pacific Northwest. Table 1 lists the primary biomass produced annually by regions, as well as the area in square kilometers of each region.

Trophic Position

To determine the average trophic position of the removals in each region, the total removals were partitioned into three trophic groups and each group was assigned a typical trophic position. An exponential average trophic position was calculated by multiplying the antilog of the trophic position by the biomass in that trophic group, summing, dividing by the total biomass, and taking the log of the result.

The total removals were taken as the sum of U.S. commercial landings, U.S. recreational landings, foreign catch off U.S. shores, and by-catch discards. The U.S. commercial landings (NMFS, 1975) and the foreign catch (Statistics and Market News Division, 1975) are based on 1972 statistics. The U.S. recreational landings are based on 1970 statistics (Deuel, 1973). The by-catch discards were representative estimates (MARMAP, 1975). U.S. commercial landings are adjusted to round (live) weight including weight of mollusc shells.

The total removals were 8.30 BU, ranging from 0.20 in California to 3.23 in the Pacific Northwest. The U.S. commercial landings totaled 2.42 BU; the U.S. recreational landings totaled 0.72 BU; the foreign catch totaled 3.67 BU and the discards totaled 1.5 BU. Table 2 lists the removals, partitioned by region and by source.

The three trophic groups used are:

A - sedentary filter feeders, assigned a trophic position of 1.0 (herbivores);

B - non-sedentary filter feeders, assigned a trophic position of 1.5 (between herbivores and first level carnivores); and

C - predators, assigned a trophic position of 3.0 (second level carnivores).

Group A totaled 0.8 BU; group B totaled 1.5 BU; and group C totaled 6.0 BU. The lumped average trophic position for the area of our consideration was 2.865. The average trophic position by region ranged from 2.747 for the Gulf of Mexico to 2.974 for the Pacific Northwest. Table 3 lists the total removals partitioned by region and by trophic group as well as the average trophic position by region.

Other Inputs/Outputs

There are several sources of inputs and outputs other than the primary biomass produced by photosynthesis and the removals by man. Some of these are:

- a. Advection of primary biomass into or out of the region;
- b. advection of detrital biomass into or out of the region;
- c. migration of biomass into or out of the region;
- d. eviscera and other parts of the removals discarded at sea; and
- e. by-catch discards.

While there is tremendous advection of water into and out of some regions by currents such as the Gulf Stream, for a first approximation I considered that the primary biomass advected into a region will be approximately equal to that advected out of the region. Advection of detrital biomass into the regions is primarily by estuarine and river runoff. As a first approximation, these components of "other inputs/outputs" were not included. Migration of biomass into the regions is by pelagic species such as tuna that may gain the major portion of their biomass by feeding outside of the region. This component of the "other inputs/outputs" also was excluded because the total component of the removals in this category is a relatively small fraction of the whole. Eviscera and other parts discarded at sea may be an important fraction of the "other inputs/outputs." In the first approximation, this component also was excluded.

The only input/output used to determine a correction to the primary biomass in each region is the by-catch discards. These discards were assumed to be fed upon by detrital feeders which had been lumped into group C, predators with a typical trophic position of 3.0. This implies that the discards enter the system at a trophic position of 2.0; this was used in the calculation of corrections to primary biomass (eq 6). The corrections to primary biomass total 50.0 BU and range from 6.0 BU in California to 33.3 BU in the Gulf of Mexico. Table 4 lists the correction to the primary biomass and the corrected primary biomass by region.

RESULTS

Equation 5 was used to calculate potential harvestable production at the average trophic position of the present removals for each region and for the total area. The total potential harvestable production for the whole area is just under 13 BU. The potential, by regions, ranges from 0.7 BU in California

to 4.5 BU in the Pacific Northwest. The surplus was calculated as the difference between the potential and the present removals. The total surplus is about 4.5 BU, ranging, by regions, from 0.5 BU in California to 1.3 BU in the Gulf of Mexico. Table 5 shows the harvestable production and the surplus by regions.

The surplus was entered into eq 5 at the average trophic position of each region and used to calculate the amount of primary biomass that would be needed to obtain just the surplus. This was then used to calculate the surplus, if it could be harvested, at trophic positions of 1.0, 1.5, and 3.0. The total surplus harvestable at a trophic position of 1.0 is over 150 BU and ranges from 19 BU in the North Atlantic to 55 BU in the Pacific Northwest. If harvested at a trophic position of 1.5, the total surplus is about 60 BU, ranging from 7.5 BU in the North Atlantic to 21 BU in the Pacific Northwest. At a trophic position of 3.0, the total surplus is reduced to 3.5 BU, ranging from 0.4 BU in the North Atlantic to 1.2 BU in the Pacific Northwest. These results, a consequence of the exponential nature of the model, are shown in table 6 in which the surplus is tabulated as a function of trophic position by region.

This last presentation ignores the way in which the ecosystem expresses itself. It is unlikely that the surplus in any region can be harvested in a particular trophic group of our choice. The analysis does point out that the most significant way to increase the potential harvest is to reduce the average trophic position of the removals. But how much can that average trophic position be reduced? If 10% of the total biomass presently being removed were to be shifted from trophic group 3.0 to trophic group 1.0, the average trophic position would be reduced by about 3% and the potential harvest would be increased by about 15%.

It seems reasonable to state that potential production cannot be increased by more than 50% by shifting the harvest to a lower average trophic position. This would bring the total potential to less than 20 BU, ranging from 1.1 BU in California to 6.8 BU in the Pacific Northwest. The surplus would then be about 11 BU, ranging from 0.9 BU in California to 3.6 BU in the Pacific Northwest.

What if we have over estimated the primary biomass by an error of 25%. Certainly our estimate should be better than that. This would reduce the potential harvest by 25%, bringing the total down to about 9.5 BU. The range, by regions, would be 0.6 BU in California to 3.4 BU in the Pacific Northwest. The surplus would then be 1.3 BU, ranging from slightly negative in the North Atlantic to 0.5 BU in the Gulf of Mexico.

Table 7 lists the potential harvestable production and the surplus by regions with a range of 75% to 150% of the potential.

The model, with inputs used in this analysis and the ranges estimated above, gives an upper limit of harvestable living marine resources from waters off the U.S. coast of about 13 BU, with some possibility that the limit may be as high as 20 BU or as low as 9.5 BU. The surplus over present removals, 8.3 BU, is about 4.5 BU with a range of 1.3 BU to 11 BU.

REFINEMENTS

The results obtained by this use of the model indicate that the waters off the U.S. coasts are not a boundless cornucopia of living marine resources. There are limits to the potential production from these waters and these limits may be very close to the present removals. It is therefore appropriate to consider refinements to the model that can help provide a better estimate of the limits to potential production.

Because of the exponential nature of the model, the most important components are the actual transfer efficiency as a function of trophic position and the trophic position of the present removals. A better estimate of average trophic position of present removals can be made by assigning typical trophic positions to each species or species group in the removals. The efficiency of transfer is much more difficult to estimate, but trophodynamic studies will help to improve the estimates.

The amount of primary biomass produced by photosynthesis and the fraction of production available to man are the next most important components of the model. Better estimates of the primary biomass produced by photosynthesis can be obtained by a re-analysis of all available primary production data. The fraction of production available to man, taken as 0.5 in this model, was based on estimates from the Peruvian anchovy fishery. This fishery, a highly variable fishery based on short-lived species with a low trophic position, is not typical of the world fisheries or of those in waters off the U.S. coasts. A better estimate of available fraction can be obtained from studies on the major components of the present removals.

The remaining important refinement to the use of the model is to obtain better estimates of "other inputs/outputs", in particular, of the amounts of primary biomass and detrital biomass advected into or out of the regions of consideration.

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Table 1.--Primary biomass by region.

Region	Area (km ² x 10 ⁶)	Photosynthetic rate (tC/km ² yr)	Primary carbon fixed ((tx10 ⁶)C/yr)	Primary biomass (BU)
North Atlantic shelf estuaries	0.27 0.06 <u>0.33</u>	105 237	28.35 14.22 <u>42.57</u>	851.4
South Atlantic shelf Gulf Stream	0.18 0.09 <u>0.27</u>	105 49	18.90 4.41 <u>23.31</u>	466.2
Gulf of Mexico shelf estuaries	0.38 0.02 <u>0.40</u>	105 237	39.90 4.74 <u>44.64</u>	892.8
California shelf current	0.10 0.10 <u>0.20</u>	105 28	10.50 2.80 <u>13.30</u>	266.0
Pacific Northwest shelf estuaries	0.82 0.04 <u>0.86</u>	105 237	86.11 9.48 <u>95.59</u>	1911.8
Total	2.06		219.41	4388.2

t - metric tonne BU - Biomass unit (10⁶ metric tonnes per year) C - carbon

Table 2.--Total removals by source and by region.

Region	U.S. commercial landings	U.S. recreational landings	Foreign catch off U.S. shores	Discards	Total
	(BU)	(BU)	(BU)	(BU)	(BU)
North Atlantic	1.008	0.233	0.962	0.15	2.35
South Atlantic	0.148	0.183	0.0	0.15	0.48
Gulf of Mexico	0.820	0.221	0.0	1.00	2.04
California	0.152	0.043	0.0	0.0	0.20
Pacific Northwest	0.292	0.036	2.704	0.20	3.23
Total	2.420	0.716	3.666	1.50	8.30

Table 3.--Total removals by group

Region	Group A T.P. = 1.0 (BU)	Group B T.P. = 1.5 (BU)	Group C T.P. = 3.0 (BU)	Total removals	T.P
North Atlantic	0.470	0.547	1.333	2.35	2.761
South Atlantic	0.029	0.056	0.396	0.48	2.918
Gulf of Mexico	0.182	0.745	1.113	2.04	2.747
California	0.007	0.041	0.152	0.20	2.885
Pacific Northwest	0.124	0.064	3.042	3.23	2.974
Total	0.812	1.453	6.035	8.30	
Lumped	0.812	1.453	6.035	8.30	2.865

A--sedentary filter feeders.

B--non-sedentary filter feeders.

C--predators

T.P.--Trophic position

Table 4.--Corrections to primary biomass and corrected primary biomass.

Region	Primary Biomass	Discards	Correction to primary biomass	Corrected primary biomass
	(BU)	(BU)	(BU)	(BU)
North Atlantic	851.4	0.15	5.0	856.4
South Atlantic	466.2	0.15	5.0	471.2
Gulf of Mexico	892.8	1.00	33.3	926.1
California	266.0	0.00	0.0	266.0
Pacific Northwest	1911.8	0.20	6.7	1918.5
Total	4388.2	1.50	50.0	4438.2

Table 5.--Potential production and surplus.

Region	Corrected primary biomass (from table 4)	Average trophic positions (from table 2)	Potential harvestable production (from eq. 6)	Removals (from table 3)	Surplus (potential minus removals)
	(BU)		(BU)	(BU)	(BU)
North Atlantic	856.4	2.761	3.03	2.35	0.68
South Atlantic	471.2	2.918	1.24	0.48	0.76
Gulf of Mexico	926.1	2.747	3.37	2.04	1.33
California	266.0	2.885	0.74	0.20	0.54
Pacific Northwest	1918.5	2.974	4.53	3.23	1.30
Total	4388.2		12.91	8.30	4.61
Lumped	4388.2	2.865	12.76	8.30	4.46

Table 6.--Potential surplus production as function of trophic position.

Region	Surplus (from table 5)	Average trophic position (from table 2)	Surplus if harvested at 1.0	Surplus if harvested at 1.5	Surplus if harvested at 3.0
	(BU)	(BU)	(BU)	(BU)	(BU)
North Atlantic	0.68	2.761	19.20	7.44	0.43
South Atlantic	0.76	2.918	28.91	11.20	0.65
Gulf of Mexico	1.33	2.747	36.58	14.17	0.82
California	0.54	2.885	19.30	7.47	0.43
Pacific Northwest	1.30	2.974	55.00	21.30	1.24
Total	4.61		158.99	61.58	3.57
Lumped	4.46	2.865	153.44	59.43	3.45

Table 7.--Range of potential production and surplus

Region	Potential	+50%	-25%	Removals	Surplus	Maximum	Minimum
	(BU)	(BU)	(BU)	(BU)	(BU)	(BU)	(BU)
North Atlantic	3.03	4.55	2.27	2.35	0.68	2.20	-0.08
South Atlantic	1.24	1.86	0.93	0.48	0.76	1.38	0.45
Gulf of Mexico	3.37	5.06	2.53	2.04	1.33	3.02	0.49
California	0.74	1.11	0.56	0.20	0.54	0.91	0.36
Pacific Northwest	4.53	6.80	3.40	3.23	1.30	3.57	0.17
Total	12.91	19.38	9.69	8.30	4.61	11.08	1.39
Lumped	12.76	19.14	9.57	8.30	4.46	10.84	1.27

AN ASSESSMENT OF ENVIRONMENTALLY RELATED VARIATION IN
THE RECRUITMENT OF THE CALIFORNIA CURRENT STOCK OF
PACIFIC MACKEREL AND ITS IMPLICATIONS FOR MANAGEMENT

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ABSTRACT ONLY

Long-term oceanographic and meteorological data were used to develop models that describe the observed variation in the recruitment of Pacific mackerel (*Scomber japonicus*) in the California Current region. The models that were found to best describe recruitment included both density-dependent factors and environmental factors. Models incorporating only density-dependent factors accounted for a maximum of 24% of the observed variation in recruitment. Multiple regression models including both density-dependent and environmental-dependent factors were fitted to the data available for two time periods: 1931-68 and 1946-68. A model including three environmental factors and a density function was selected as the best fit to the longer period. In this model increased recruitment was associated with increased sea surface temperature, reduced sea level, and reduced atmospheric pressure during the spawning season. This model accounted for 59% of the variation in recruitment for 1931-68. The model fitted to the 1946-68 period included a density function and two environmental factors, on which data was not available prior to 1946. Increased recruitment with this model was associated with increased coastal upwelling and decreased offshore convergence during the spawning season. This model accounted for 76% of the variation in recruitment for 1946-68.

Yields from recruitment simulations were greatly different from yields from dynamic pool simulations. Maximum yield with a yield per recruit model occurs with an age at recruitment of 1 or less and instantaneous fishing mortalities (F) in excess of 1.0. Dynamic pool simulations that incorporate a Ricker spawner-recruit function predict that extinction of the stock will occur with the above fishing strategy. Dynamic pool simulations with both density-dependent and environmental-dependent recruitment functions were assessed to determine maximum yield with different ages at recruitment and different quota options.

ATMOSPHERE-OCEAN INTERACTION

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This paper attempts to present some of the basic concepts underlying the studies of large-scale air-sea interaction being conducted by the NORPAX project and the Climate Research Group at the Scripps Institution of Oceanography. Since most of the material used in this synopsis has appeared elsewhere, only a summary is given here and reference is made to publications which delve more deeply into the various topics.

For the past 10 years or so, Dr. Jerome Namias has been examining the influence of the oceans on the weather and climate of continental areas, first as Chief of the Extended Forecast Division of the U. S. Weather Bureau and more recently at Scripps (Namias 1975a). His group is a part of the NORPAX program, but has other areas of interest as well. The primary emphasis has been on large-scale air-sea interaction in the North Pacific and the resultant downstream effects on North American weather and climate. Since this symposium is directed toward marine fisheries, the major emphasis here is on the possibilities of forecasting near-surface ocean temperatures, a parameter of interest to those who attempt to assess Albacore tuna and other fisheries.

There are several approaches to modelling the atmosphere and the oceans. We have chosen an empirical-statistical-physical approach to the problem for several reasons:

- 1) Progress in coupled numerical dynamical models is slow, laborious, and expensive. There is some question as to whether this approach will prove fruitful beyond two or three weeks.
- 2) The bulk formulae representing air-sea heat exchange still are not ideally suited to time and space averaged data.
- 3) The dominant large scale mechanisms and processes connecting the ocean and atmosphere are still poorly understood and parameterized.

Our approach is based upon the use of statistical tools to help identify dominant physical processes, to delineate key geographic areas, and to estimate the relative roles of various hypothetical coupling mechanisms. We are currently using correlation, multiple regression, and empirical orthogonal function techniques, but other analysis and modelling approaches are being explored.

We feel the optimum method for longer range prediction will probably be some form of coupled statistical-dynamical model. At the moment, we are still trying to determine exactly what should be included in such a model.

In our analyses we use anomalies or differences from long-period (20 to 26 year) means to look at differences from the normal annual cycle. Compared to the annual cycle these differences represent the significant changes in weather and climate from one year to the next. One of the first illustrations of the value of anomaly patterns is shown in figure 1 (Isaacs 1968). A fairly coherent area of above normal, sea surface temperature departure from the mean (SST_{DM}) seems to migrate from west to east across the northern Pacific for a period of nearly two years. An intensifying, anomalously cold patch grows behind the warm area. Isobars of sea level pressure departure from the mean (SLP_{DM}) have been superimposed. The arrows indicate the direction of anomalous atmospheric flow. An apparent interlocking of ocean and atmosphere anomaly patterns, with flow from the south over warm areas and flow from the north over cold areas, is fairly obvious. As you can see we are examining features of large areal extent which seem to persist over time periods of seasons, years or longer.

Examination of long period means of winter SLP (fig. 2) can give an indication of the spacial scale in the atmosphere (Namias 1975b). There are three main features in the mean winter pattern: the Aleutian or North Pacific Low, the Icelandic Low, and the Siberian High pressure areas. Since the Aleutian Low has two predominate modes, a single low pressure area centered over the Aleutian chain, and a split pattern with one low in the Gulf of Alaska and the other east of Kamchatka, the long period average smears into the pear-shaped contours observed in the North Pacific. Examination of standard deviations of winter SLP (fig. 2, right) indicates that the Siberian High is a relatively static feature, the Icelandic Low varies somewhat in strength, but the most intense variations occur in the area of the Aleutian Low. The high standard deviation over the Himalayas is probably associated with altitude corrections to the observed pressures.

If we compute simple correlation coefficients of the same or different parameters between one geographic grid point and surrounding grid points, patterns such as those in figures 3 and 4 emerge (Namias and Born 1972). Comparison of these patterns indicates comparable size scales for 700-mb height and SST, but with differences from one locality to another. There are also differences among seasons (not shown). The intricate interdependence of SST and 700-mb height is hinted at in the lower sections of figures 3 and 4, but we will not discuss this feature here other than to point out that this too is a function of geographic location, time of year and, to some extent the initial conditions of ocean atmosphere.

To get a feel for the time scales involved, we can correlate values at all of our $5^\circ \times 5^\circ$ geographic grid points with the same grid points at various lags for our three basic parameters, lumping all months together. This technique can be referred to as pattern correlation. It becomes readily apparent (fig. 5) that SST anomaly patterns have a much longer lifetime than do the atmospheric patterns. This would be expected from the high heat storage

capacity and relatively sluggish circulation of the ocean. Atmospheric parameters die away in less than two months. Note, however, the slightly greater persistence in 700-mb height correlations. A large amount of this increased pattern correlation has been ascribed to hydrostatic effects from SST anomalies (Namias and Born 1970).

The pattern correlations lead us to assume that the ocean is static. While the currents are relatively slow in the central ocean, their effects on redistribution of anomalous heat content become large at time periods of seasons or longer. Thus, if we compute the monthly mean SST anomaly averaged over the entire North Pacific (north from 20°N) and derive lagged autocorrelations, we observe (fig. 6) that the persistence of ocean average SST_{DM} is significantly higher than the persistence of non-moving patterns.

In these correlations all months are lumped together. Since we already know that there are seasonal differences in the spacial distributions, it is profitable to separate the pattern correlations into monthly components. When we compare each month with the lumped pattern correlation (fig. 7), the higher values appear in the cold seasons and the lower values generally occur in the warm seasons. By examining the figure a little more closely, one can see that there is a tendency for patterns generated or occurring in one cold season to recur during the next cold season. There is some indication of recurrence in the second cold season also.

We have put forward the hypothesis (Namias and Born 1974) that cold season SST anomalies are often indicative of deep, wind-mixed heat anomalies which tend to be covered over and masked by a shallow surface layer in summer. As the fall storms begin to pass through and the zonal wind speed (fig. 8) increases in September, these hidden anomalies are stirred back up to the surface. This mechanism which possibly accounts for the recurrence of anomaly patterns in the cold season can be illustrated by an example of a hidden anomaly taken from the aircraft XBT program in NORPAX (Barnett 1976). The temperature vs. depth profile along 170°W (fig. 9) in August 1975 shows a cold anomaly at the surface from about 33° to 40°N , with an underlying stratum as much as 3°C above normal. As wind driven mixing increases in September (fig. 10) the surface layer is beginning to break down and the warm subsurface anomalies have coalesced. By October 1975 (fig. 11) the cold water at the surface has disappeared and the warm core has been mixed to the surface.

So far only monthly or seasonal time scales have been discussed. Persistence and recurrence also are apparent at longer time scales in both the ocean and atmosphere. For instance, a graph of winter mean air temperatures at 3 widely spaced cities in the southeastern U.S. (fig. 12) shows that there was a sharp decline in temperature from 1957 to 1958, relatively cold winters through the 1960s, and a sharp increase in the 1971-72 period to a warmer winter climate (Namias 1976). Tracing these and other temperatures back in time yields a similar pattern of quasi-stable climatic regimes separated by sharp breaks in the pattern. The regimes seem to last on the order of 7 to 15 years. There does not seem to be any regular periodicity, nor is there any obvious correspondence to sunspot cycles. These climatic shifts are not limited to a small

area; they are at least of hemispheric and probably of global extent. Sometimes the shifts occur at the same time the west coast of South America is experiencing an occurrence of El Niño.

The interrelationship between the North Pacific ocean and the overlying atmosphere at these longer time scales is illustrated diagrammatically in figure 13. Here the average SST anomaly for the winters of the 1960s is contrasted with the winter of 1971-72. The patterns are nearly reversed. Also shown is the mean path of the jet stream, used here only as an indicator of the dominant Rossby wave and prevailing storm track and circulation. In this figure it can be seen that the winters of the 1960s were characterized by a warm, southerly flow over the western U.S. and cold, polar air over the east. The situation in 1971-72 was basically opposite. This comparison becomes even more striking when we compare Pacific and U.S. temperatures for the winters of 1969-70 and 1971-72 (fig. 14), the years preceding and following the most recent climatic shift. Here again we see basically opposite anomaly patterns.

As a first step toward quantifying these empirical relationships, we have derived sets of statistical specification and prediction equations using stepwise multiple regression techniques. One of these sets of equations is the specification of SST from 700-mb height. The SST patterns which would be expected to exist in the presence of the observed 700-mb height for the same two winters of 1969-70 and 1971-72 (fig. 15) are quite similar to the observed SST_{DM} patterns (Dickson 1974). Actual forecasting of SST_{DM} from the prior season's observed SST_{DM} field also yields encouraging results. The only illustration of this technique available (fig. 16) indicates that using the multiple regression (screening) technique as a forecast is superior to using either the climatological normal as the forecast or the assumption that the prior SST_{DM} pattern will persist unchanged.

In the preceding we have tried to demonstrate that the near surface ocean and atmosphere are normally closely linked on space scales of hundreds to thousands of kilometers and time scales of months to decades. Results to date strongly indicate that the future thermal state of the near surface layers of the ocean can be forecast from knowledge of the present state of ocean and atmosphere.

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Figure 1.--Departure of sea surface temperature (°F) from 1947-58 mean.

r 700 mb at diamond vs. 700 mb elsewhere (Winter Months)

r SST at diamond vs. SST elsewhere (Winter Months)

r SST at diamond vs. 700mb elsewhere (Winter Months)

Figure 3.--Contemporaneous correlations between 40°N - 170°W (diamond) and elsewhere for 700-mb heights (upper), sea-surface temperatures (SST) (middle), and SST vs. 700 mb (lower). Shaded areas represent correlations exceeding 1% level of significance—positive correlations stippled, negative hatched.

$\approx$ 700 mb at diamond vs. 700mb elsewhere (Winter Months)

$\approx$ SST at diamond vs. SST elsewhere (Winter Months)

$\approx$ SST at diamond vs. 700mb elsewhere (Winter Months)

Figure 4.--Same as figure 3 except diamond at 40°N-130°W.

Figure 5.--Overall autocorrelations of standardized values of monthly mean sea-surface temperature (SST), 700-mb height, and sea-level pressure (SLP) determined from a 5° grid of points covering the North Pacific (north of 20°N) during the 20-year period 1947-66.

Figure 6.--Overall autocorrelations of monthly mean SST departures from the 1947-66 mean for the North Pacific (north of 20°N) determined from an area-weighted 5° grid of points. Data include the years 1947-72 except for 1968, 1969, and the first 6 months of 1970, when western Pacific data were not available; pattern correlations extended from figure 5.

Figure 7.--Autocorrelations of North Pacific mean monthly SST anomalies according to initial month. Stippled areas greater than overall correlation shown in figure 6 (upper curve), hatched areas lower.

Figure 8.--Normal annual course of the strength of the 700-mb zonal westerlies (meters per second) over the North Pacific between 35° and 55°N from longitude 130°E to 110°W.

Figure 9.--Vertical cross-section of ocean temperature anomaly along 170°W from 30° to 50°N for August 1975 from aircraft XBT drops every 80 km. Anomalies are differences from means derived from all historical data near the cross-section.

Figure 10.--Same as figure 9 except September 1975.

Figure 11.--Same as figure 10 except October 1975.

Figure 12.--Winter mean temperatures at three southeastern U.S. stations.

Figure 13.--Diagrammatic representation of average sea and atmosphere conditions for the winters of the 1960s and the winter of 1971-72.

Figure 14.--Air and sea temperature anomalies ($^{\circ}\text{F}$) for the eastern North Pacific and continental U.S. for the winter seasons of 1969-70 and 1971-72.

Figure 15.--Patterns of sea surface temperature anomaly ($^{\circ}\text{F}$) specified from the observed distribution of 700-mb height for the winters of 1969-70 and 1971-72 compared to observed temperature distributions.

Figure 16.--Root mean square error (RMSE) for predictions of January SST based on December SST in the North Pacific east from 180° . Screening procedure is compared with results obtained by forecasting the normal and by persistence. (Ordinate in RMSE in $^{\circ}\text{F}$.)

DEVELOPMENT OF A CLIMATE PROGRAM,
AN AID TO RESOURCE MANAGEMENT

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The attention focused on the world food and energy situation has raised the level of concern about climatic impacts. Climate has indeed exacerbated a growing problem of feeding and making comfortable a world population that is growing in number and in affluence. It is no surprise that a series of climate-related events seriously affecting the production of food and energy by the United States and other nations in recent years has triggered an interest in developing a means to cope with climatic variations. See, for example: National Academy of Science (1974, 1975); World Meteorological Organization (1975); U.S. Domestic Council (1974); and U.S. House of Representatives (1975, 1976). Responsibility in planning for the coping mechanisms rests within the United Nations and in the countries concerned.

AN OVERVIEW

The climate impact problem can be divided into three basic elements: impact analyses and risk assessments, where the information necessary for developing and implementing policy is assembled and disseminated; modeling and prediction research, where an understanding of the governing laws of climate are sought and where a prediction capability is pursued; and observations and monitoring, where climate process field studies are carried out, where climatic elements and their changes are described, and where data are collected, processed, distributed, and archived. These are shown in the accompanying Venn diagram (fig. 1). Within the outer ring of the diagram are the international organizations that have a major interest in the respective subject elements. In the center circle are U.S. Governmental agencies that have a significant interest in solving problems related to any of the three respective topics.

For example, under Impact Assessments, the Energy Research and Development Administration (ERDA) is interested in climatic variability as it relates to developing new energy sources; the National Oceanic and Atmospheric Administration (NOAA), in consultation with the Department of Agriculture and other appropriate agencies, attempts to develop information on climate relevant to health, agricultural productivity, availability of water resources, and fuel distribution or demand; and the new National Science Foundation (NSF) Office of Climate Dynamics plans to encourage basic research in this area. The United Nations Food and Agriculture Organization (FAO) and the World Meteorological Organization (WMO) are developing the concepts for an international system for early warning of food shortfalls due to variations in weather and climate. The United Nations Environment Program (UNEP) hopes to encourage

Figure 1.--The major elements and participants in climate programming

all of the international efforts in climate research and monitoring and impact analyses to provide a continuing assessment of climatic impacts on the global environmental system. The International Federation of Institutes for Advanced Studies (IFIAS), one of two nongovernment institutions cited on the diagram, is employed in a study to determine the social, economic, and ethical dimensions of the effect of climate changes.

In the modeling and prediction research section of the diagram, we note that the National Aeronautics and Space Administration (NASA), NOAA, and NSF are active in developing climate models that aim to understand the physical basis of climate and, too, the potential inadvertent changes to climate that are threatened by man. The World Meteorological Organization (WMO) and International Council of Scientific Unions (ICSU) are developing plans for a Global Atmospheric Research Program (GARP) objective of reaching a better understanding of the physical basis of climate. These plans will encourage the development of climate models and large-scale weather/climate process-oriented field studies. The latter fall in the next category of observations and monitoring.

In the observations section of the diagram, ERDA is mentioned for providing observations of stratospheric transport processes and measurements of high altitude trace constituents. NASA has assumed a lead role in developing satellite-based techniques for remote sensing of stratospheric trace

constituents and is experimenting with Earth energy budget observation systems. The Department of Defense (DOD) Office of Naval Research, with the NSF, participates in the North Pacific Experiment, aimed at understanding the oceanic processes that are both part of and a factor in affecting climate. NOAA operates four atmospheric baseline observatories from Point Barrow, Alaska, and Mauna Loa, Hawaii, to American Samoa, and Antarctica. NOAA also provides the vast data management required for climate studies, and NSF, through its International Decade of Ocean Exploration, has supported the collection and analysis of deep sea cores that reveal much of the Earth's climatic history. In addition, a considerable amount of work has been done by the Aspen Institute and Rockefeller Foundation in assessing climate impacts, by the Department of Defense in ocean monitoring, and by the Environmental Protection Agency in support of work to develop air pollution climatologies and to assess the impact of pollutant and thermal emissions on climate.

The effectiveness of all this activity has been examined by several panels within the past few years. One common conclusion is that interdisciplinary planning and participation across many of the interfaces of this diagram need improvement. To illustrate, let us see where the interfaces are well connected: through the professional scientific channels, national and international research results are exchanged freely. Domestically, the National Advisory Committee on Oceans and Atmosphere (NACOA) and the National Academy of Sciences (NAS) may examine or review the total spectrum of climate interests in an advisory capacity. In fact, at last count there were approximately twenty panels within the Academy examining at least some part of the climate issue. In general, *information exchange* across these boundaries is adequate, both domestically and internationally. Also, the mechanisms exist to *plan* international programs directly over these interfaces. Domestic *planning*, however, is not so direct.

CLIMATE PROGRAM PLANNING IN THE UNITED STATES

No single Federal body views the climate effort as a coherent program. No responsible body exists at the program planning level to maintain official cognizance of this array of climate programming, to coordinate the Federal activities across all these interfaces, and to recommend program adjustments where necessary. Because of this and other inadequacies in climate programming pointed out by several reviewing panels including Interdepartmental Committee on Atmospheric Sciences, NACOA, and the NAS, the U.S. Domestic Council prepared a report, *A United States Climate Program*, which answers these criticisms.*

Recent Federal planning efforts have emphasized a balanced program of climate observations and monitoring, research and impact assessments. (See block diagram, figure 2.) The objective of such a broad climate program is to

*A note added May 1976: Two bills have been introduced in Congress to implement a National Climate Program (HR 10013 and HR 13736). Hearings on these bills were held in May, 1976, before the Subcommittee on the Environment and Atmosphere of the House Committee on Science and Technology.

Figure 2.--Supporting elements in a climate program

provide climate information in a form suitable for developing and implementing policy in the management of National resources. Thus, the program output is shown in the category of Climate Impact Analyses and Climate Risk Assessments. To provide this service, an up-to-date statement on the character of climate is necessary. This can be provided by a combination of modeling, statistical and empirical analyses, and actual observations. Observations and monitoring of climate directly or indirectly are required to maintain a current awareness of the climate state. The Earth's energy budget and the elements that affect it must be observed routinely; observations should include the receipt of solar energy, and the spectral energy distribution, stratospheric and tropospheric photochemical and dynamical processes, the albedo of the Earth's surface and the heat storage and transport within the world's oceans. The underpinning of the climate program is the existing climate data base and worldwide weather observing system, the advanced technology in computer systems and satellite measurement techniques, and in scientific interest and capability.

The report of the Domestic Council's Subcommittee on Climate Change, submitted in December, 1974, recommended a four-point program to develop a climate impact assessment program, improve existing climate prediction

techniques, develop numerical modeling techniques for simulation and prediction of climate, and develop a global monitoring system for climate.

Several products or services would come from the first two of these points. Many specialized data composites would be made available for research or assessment purposes; analyses of domestic and worldwide climatic conditions would be updated frequently as support for crop/climate risk assessments, fishery impact studies, fuel distribution planning, and other applications. A greater effort would be expended, largely through stimulation of research under grants and contracts, to improve the current monthly and seasonal temperature and precipitation outlooks issued by the National Weather Service and to extend the area of interest to provide global climate outlooks. Interannual climate prediction techniques would be investigated.

Under the third program element, existing numerical models would be applied to experimental monthly climate forecasts, the development of coupled ocean/atmosphere models and climate predictability studies would be encouraged, and various model sensitivity studies and experiments to simulate societal impact on climate would be supported.

The fourth program element would develop a global climate monitoring system with emphasis on oceanic processes, the Earth's energy budget, and atmospheric baseline characteristics to fill major gaps in the current climate data base. Attention would first be directed to obtaining a data base of global sea surface temperatures, with satellite technology as the principal tool. Development of techniques for obtaining subsurface temperature and salinity profiles through the mixing layer, and large scale air/sea process-oriented field studies would be given high priority. Satellite applications for monitoring components of the Earth's energy budget and climatic indices, such as cloud cover and sea ice extent, would be supported. Stratospheric and tropospheric baseline observation, monitoring, and assessment programs would be expanded as well.

To manage such a program, the Domestic Council report recommends that: the Department of Commerce be designated the program coordinating agency; an Interagency Climate Program Management Review Board be established; multiple agency funding be provided directly to the participating Federal agencies; the Office of Management and Budget annually review the program; an annual plan be prepared by NOAA with the assistance of all participating agencies; and a nongovernmental advisory body periodically review the progress and plans concerning the research aspects of the U.S. Climate Program.

Continuing analysis of Agency programs and development of program plans is under way by an interagency climate program planning group under the Interdepartmental Committee for Atmospheric Science. The report of that group will develop in greater detail the strategy for implementing a national program in climate. Hopefully, through all of these efforts, a focus for climate-related science and applications can be established.

A NOAA climate program plan was drafted in May 1975. Climate, in the context of the NOAA plan, is defined to include the statistics of atmospheric and oceanic processes in time units of at least two weeks, the theoretical limits of day-to-day weather predictability, and at ranges of weeks, months, years, or longer. The proposed program integrates the capabilities and responsibilities of NOAA with those of other agencies, following the concept of a broad balanced program described earlier. Its objective, to keep abreast of, and anticipate, climatic variations and their impacts, can be reached by developing and applying knowledge of the processes of climatic variability and its effect on human affairs and identifying man's impact and potential influence upon regional and global climate.

Impact Analyses, Risk Assessments, and Current Awareness of Climate

Returning again to figure 2, the NOAA program assessments of climate impacts and risks are to be made primarily at the Environmental Data Service's Center for Climatic and Environmental Assessment with support from the Environmental Studies Service Centers of the National Weather Service and the Environmental Groups of the National Marine Fisheries Service. Current awareness of the climatic state would be provided through the proposed Climate Diagnostics Center (CDC), an interactive program center consisting of specialists gathered, in a programmatic sense, from existing EDS, ERL, NESS, NMFS, and NWS programs. The CDC will serve as a focal point for continuing application of new technology and new approaches to climate diagnostics and predictions.

Prediction

A best estimate of the climatic state and outlook is all that is possible at this time. Improvement of existing capabilities to identify and anticipate regional and global climate is being approached from two directions: first, from deterministic modeling, which attempts to solve the governing laws of physics, and the second, from empirical or statistical studies based on the observed past climatic behavior. The Environmental Research Laboratories' Geophysical Fluid Dynamics Laboratory is the principal NOAA facility addressing the modeling question and the Long-range Prediction Group of the NWS pursues the latter course.

The first approach, if successful, would prove to be the most valuable. Unfortunately, this approach also offers the least hope of being solved entirely. We have a small probability of meeting complete success, but a very great payoff is likely should the objective be reached. Success, however, must be measured in degrees. Already, deterministic modeling is providing valuable insight into such problems as inadvertent modification of the stratosphere and in the design of cost-effective climate observing systems. Significant benefits can be realized quickly; for example, helping to define approaches to research and observation problems, as in the design of an ocean climate observation system.

The second approach is meeting with some limited success today. Additional support should improve the accuracy of current monthly and seasonal

outlooks and will aid in making assessment of climatic risk and maintaining an awareness of the climatic state. Both approaches will be supported by NOAA. Both offer advantages with immediate as well as long-term benefit.

Observations and Monitoring

Climate services can be improved immediately by expanding the search for and acquisition of historical climate data. These can be done inexpensively within existing programs. Considerable reprogramming has been accomplished already to handle some of these tasks within the EDS.

There are significant elements of climate about which relatively little is known. These include the Earth's energy budget and the "baseline" or natural state and behavior of the coupled ocean-atmosphere system. For significant progress to be made in climate modeling and in maintaining an awareness of the climatic state, present observational methods must be improved. Programs within EDS, ERL, NMFS, NESS, and NOS apply. Requirements specifically to be addressed in the first phase of the NOAA program are: a better understanding of the equatorial Pacific, large scale air-sea coupling processes important in affecting climate (through a field research project); a comprehensive study of the needs for global ocean observations and the best methods to satisfy them; development of a satellite-based solar and Earth radiation monitoring project; completion of facilities for the atmospheric baseline observatories (Point Barrow, Alaska; Mauna Loa, Hawaii; American Samoa; and the South Pole); and development of a stratospheric baseline observation project. A large new data set will result and data management will fall to existing management facilities within the EDS.

Some development of technology is required for the observation program elements. For example, cost-effective methods of obtaining data from the oceans is necessary. Some in-situ observations are needed, but it is hoped that satellite remote-sensing techniques can be made more effective, particularly in interpretation of low-level winds and energy flux over the open oceans.

CONCLUSIONS

The study of climate and the application of new-found knowledge covers a broad range of interests and subjects, posing challenging management problems. Suddenly it is important to involve oceanographers in large-scale, even global, considerations of air-sea exchange processes; we are tempted to try to bring our knowledge of oceanic processes parallel to our understanding of the atmosphere too quickly. We have neither the finances nor the technology to do so and, most importantly, we have not trained enough scientists. The urgency attached to our development of an "ocean climate" subprogram is to accelerate the building of this base of our understanding of ocean-atmosphere climate processes.

Barring serendipity, we can expect a lengthy basic research problem of deterministic modeling of climate, while cognizant of the demands for ocean and atmosphere climate forecasts. Existing techniques for producing climate outlooks inherently contain a degree of uncertainty--upon which decisions must be made. A climate program must seek to improve both the technique, thereby reducing the uncertainty, *and* the way in which the "forecast" is presented to the policy or decision maker. Last, we have yet to apply the full range of climate information to problems related to food from land *and* sea, health, energy, and water resources. Here, improved communication between specialists in these various subjects can yield better-focused and better-supported applied research that in turn can yield much near-term benefit to many of our national interests.

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SUMMARY REVIEW OF
DYNAMICAL NUMERICAL MARINE ECOSYSTEM MODEL
(DYNUMES)

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INTRODUCTION

Environmental Changes as Dynamic Forces in a Marine Ecosystem

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

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

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

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

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

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

Definition of a Dynamic Marine Ecosystem Model

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

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

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

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

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

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

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

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

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

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

THE FORMULATION (DESIGN) OF THE MODEL

Conversion of Descriptive Data and the Restrained Functions

Most biological data are available in descriptive form. However, these data are needed in numerical form for use in a dynamic numerical quantitative model. In most cases, no great difficulties are encountered in making the conversion, but there is some concern about the validity of some of the quantitative

estimates. Where and when great variability in quantitative data is encountered, statistical methods will be used for deriving confidence limits or intervals. Examples of the conversion of descriptive data have been given in describing input data, such as migrations. In addition, dispersion of standing crops or species are handled with dispersion and diffusion equations and their finite difference solutions as used in numerical pollution transport and dispersion programs, with the constraint that these solutions must be conservative. The aggregation, however, must be handled with prescribed or derived movement restrained to a particular time and area. The advection equation solved and programmed by Brahm and Pedersen (fig. 8) is suitable for this purpose.

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

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

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

Flow Diagrams

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

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

Examples of Formulas Used

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

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

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

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

A schematic abbreviated listing of the relations between an ecosystem model and environmental and descriptive (conceptual) models is shown in figure 14. The environmental models provide various inputs to the ecosystem model. No

feedback is provided here, as the ecosystem does not influence the statics or dynamics of the environment (except in few cases of little consequence, such as increase of turbidity due to high phytoplankton standing crop or regeneration of nutrients). The "chemo-dynamic" approach (i.e., using nutrient availability, regeneration, etc.) is not used in the initial state of our model, because many recent attempts in this field have not led to any useful models.

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

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

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

A Normal spawning conditions
(optimum temp. 3 to 5 °C)

B Spawning displacement during positive temperature anomaly

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

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

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

Migrations,
transport,
dispersal, aggregation.

Figure 3B.--Principal processes.

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

A. Zooplankton

1. Annual production, monthly mean standing crop, consumption (copepods, euphausiids, decapods, etc.).
2. Proportion consumed by pollock (monthly variation, density, (availability) dependent).

B. Ichthyoplankton

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

C. Small pelagic fish

1. Preliminary estimates of annual distribution of abundance.
2. Availability to mammals and birds.

II. Main food web components

D. Pollock

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

E. Mammals (fur seal and bearded seal)

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

F. Birds (shearwaters, murre)

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

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

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

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

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

Isobaths

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

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

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

II. If: $T_w < T_1$, or $T_w > T_2$, then

$\frac{\partial B_t}{\partial t} = -\vec{W}$, ∇B which in forward time, backward space, finite difference approximation is: $B_{t,m}^{t+1} = (1 - \sigma) B_{t,m}^t + \sigma B_{t,m-1}^t$

III. Symbols:

T_w - actual water temperature

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

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

$T_{1a}; T_{2a}$ - the mean optimum temperature limits

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

α - phase speed (30° per month)

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

t - time

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

B_t - biomass change caused by "temperature" migrations

m - grid point

$\sigma = \vec{W} \frac{\Delta t}{\Delta x}$, Δx is grid size, Δt is time step

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

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

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

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

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

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

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

Restraining tests:

- 1) Time, if between specified limits, no computation.
- 2) Time, specified for initialization of migration to (a) shallow and (b) deep water. (Migration end determined by sign change of cosine). Migration duration prescribed by α_v .
- 3) Depth, to determine direction of migration.

III. Example of resulting migration speed and duration:

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

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

I. Initialization

- A. Prescribe monthly distribution of biomass by 4 age groups (juveniles, pre-fishery year-class(es), 2 fishable year-class groups). (Derive data from catch statistics and experimental fishery, etc.)
- B. Composition of food.
- C. Generate monthly abundance of principal food groups.
- D. Estimates of monthly growth, mortality, food, etc., coefficients.

II. Computation (nested DO loops)

I = 1, 12, 4

- A. Growth, mortality (fishing and natural) coefficients.
- B. Biomass, using A.
- C. Consumption by mammals, other fish.
- D. Distribution of remaining biomass (B-C) by
 - 1. Current (juveniles only)
 - 2. Spawning
 - 3. Temperature preference

K = 1, 4

Food consumed (total)

M = 1, 4

Various (4) food groups consumed

Summation of outputs

Portion of biomass from each age group passing to next group

Figure 11.--Generalized flow diagram of pollock subroutine.

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

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

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

- II. Presentation of annual curve of zooplankton standing crop.

$$Z_{t,m,n} = Z_{o,m,n} + Z_{c,m,n} \cos(\alpha_1 t - \mathcal{K}_1) +$$

$$Z_{s,m,n} \cos(\alpha_2 t - \mathcal{K}_2)$$

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

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

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

I. Food consumption

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

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

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

p - food coefficient for maintenance

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

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

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

II. Food composition change

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

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

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

$$B_{\text{cons}} = a0; \quad D_{\text{cons}} = b0 \quad a+b = 1$$

$$A_t = A_0 + A_v \cos(\omega t - \varphi_A); \quad B_t = B_0 + B_v \cos(\omega t - \varphi_B), \text{ etc.}$$

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

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

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

A_0, B_0 etc -annual mean of a given food item in the diet.

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

$\alpha - 30^\circ$

t - time

φ_A, φ_B - phase angle

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

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

APPENDIX A

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

1. Map factor (MF)

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

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

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

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

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

$$\begin{array}{l} I = I_p + \frac{R_E}{d} \left| \begin{array}{c} \cos \phi \\ \frac{1}{1 + \sin \phi} \end{array} \right| \cos (350 - \lambda) \\ J = J_p + \frac{R_E}{d} \left| \begin{array}{c} \cos \phi \\ \frac{1}{1 + \sin \phi} \end{array} \right| \sin (350 - \lambda) \end{array}$$

where, λ = longitude
 ϕ = latitude
 (I_p, J_p) = coordinates of north pole
 $\frac{R_E}{d}$ = distance from pole to equator in mesh lengths

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

$$\begin{array}{l} \text{Long} = \lambda = k - \tan^{-1} \left[\frac{(J - J_p)}{(I - I_p)} \right] \\ \text{Lat} = \phi = \sin^{-1} \left[\frac{R_E^2 - (I - I_p)^2 - (J - J_p)^2}{R_E^2 + (I - I_p)^2 + (J - J_p)^2} \right] \end{array}$$

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

APPENDIX B

Interpolation of data fields - Method and Theory

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

$$f_p = (1 - s) \left[(1 - r)f_0 + rf_1 \right] + s \left[(1 - r)f_2 + rf_3 \right]$$

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

- a. Vertical interpolation is performed on columns $i-1$, i , $i+1$, and $i+2$

using the formula:

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

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

where,

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

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

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

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

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

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

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

where,

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

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

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

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

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

d. Smooth $\nabla^2 A$ field for vorticity term:

$$\overline{\nabla^3 A}_0(s) = \frac{1}{9} \sum_{k=0}^8 \nabla^2 A_k = B$$

$$\begin{array}{ccc} A_6 & A_2 & A_5 \\ .6 & .2 & .5 \\ A_3 & A_0 & A_1 \\ .3 & .0 & .1 \\ A_7 & A_4 & A_8 \\ .7 & .4 & .8 \end{array}$$

e. Analyze, using extrapolated Liebmann method of relaxation to

solve Poisson equation: $\nabla^3 A = B$

but holding observed values fixed.

Note: If data distribution random, $B \approx 0$ for first pass.

(1) Iterative step:

$$A_{i,j}^{v+1} = A_{i,j}^v + R_{i,j}^v, \text{ where the residual } R_{i,j}^v \text{ can be expressed}$$

as:

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

OR over-relaxing:

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

(2) Thus:

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

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

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

f. Compute new $\nabla^2 A$

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

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

2. Main Analysis Section: (ANAL 2)

a. Compute $\nabla^2 A$ of guess field

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

$$\begin{array}{ccc} & A_2 & \\ & . & \\ A_3 & A_0 & A_1 \\ . & . & . \\ & A_4 & \\ & . & \end{array}$$

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

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

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

$$\begin{array}{ccc} \nabla^2 A_2 & & \\ \cdot & & \\ \nabla^2 A_3 & \nabla^2 A_0 & \nabla^2 A_1 \\ \cdot & \cdot & \cdot \\ \nabla^2 A_4 & & \\ \cdot & & \end{array}$$

c. Smooth the guess field

$$\begin{array}{ccccc} A_6 & & & & \\ \cdot & & & & \\ A_2 & & & & \\ \cdot & & & & \\ A_7 & A_3 & A_0 & A_1 & A_5 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ A_4 & & & & \\ \cdot & & & & \\ A_8 & & & & \\ \cdot & & & & \end{array}$$

$$\begin{aligned} A_0 \quad (s) &= A_0 + K \nabla^2 A_0 \\ &+ \frac{K}{2} \left(\frac{\partial^2 A_1}{\partial i^2} + \frac{\partial^2 A_2}{\partial j^2} + \frac{\partial^2 A_3}{\partial i^2} + \frac{\partial^2 A_4}{\partial j^2} \right) \end{aligned}$$

where

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

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

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

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

$$\begin{aligned} \nabla^2 A_0 &\sim (A_1 + A_3 - 2A_0) + (A_2 + A_4 - 2A_0) \\ &= A_1 + A_2 + A_3 + A_4 - 4A_0 \end{aligned}$$

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

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

d. Adjust the guess field with original observations:

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

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

$$\begin{aligned}
 A_{i+\Delta i, j} &\sim \frac{A_{i,j} + A_{i+1,j}}{2} + \left(\Delta i - \frac{1}{2}\right) (A_{i+1,j} - A_{i,j}) \\
 &+ \frac{\Delta i (\Delta i - 1)}{2!} \left[\frac{(A_{i+2,j} - A_{i+1,j}) + (A_{i-1,j} - A_{i,j})}{2} \right] \\
 &= A_{i,j} + \Delta i (A_{i+1,j} - A_{i,j}) + \frac{\Delta i (\Delta i - 1)}{2} \left[\frac{(A_{i+2,j} - A_{i+1,j}) + (A_{i-1,j} - A_{i,j})}{2} \right] \\
 &= A_{i,j} + \Delta i \left\{ (A_{i+1,j} - A_{i,j}) + \frac{\Delta i - 1}{4} \left[(A_{i+2,j} - A_{i+1,j}) + (A_{i-1,j} - A_{i,j}) \right] \right\}
 \end{aligned}$$

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

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

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

(2) Compute $A_{(\text{observed})} - A_{(\text{interpolated})}$.

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

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

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

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

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

where

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

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

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

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

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

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

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

$$A_o(\text{adj}) = A_o + \frac{\sum_{k=1}^k W_k D_k}{\sum_{k=1}^k W_k}$$

where K = nbr. observations affecting this grid point.

- e. Analyze, holding all adjusted values fixed, using extrapolated Liebmann method of relaxation for solution of Poisson equation $\nabla^2 A = B$. See (e) under part I. Here $\epsilon = .5$ but, again, should be data dependent.
- f. Return for 3 internal passes to steps c through e.
- g. Return for 2 external passes to steps a through f.
- h. Exit.

ANOMALOUSLY COLD TEMPERATURES IN THE SOUTHEASTERN BERING SEA
AND ALONG THE WEST COAST OF NORTH AMERICA, 1971-75

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An important example of climatic fluctuation in the Pacific Ocean is the anomalously cold water in the Bering Sea and Gulf of Alaska that Jim Johnson mentioned in his talk Monday. This cold water has been unusually persistent along the coast since at least early 1971 to date (1976). It represents a climatic fluctuation of similar magnitude but of greater duration than the well documented warm period off the West Coast during 1957-59.

Figure 1 shows time series of anomalies of sea surface temperature (SST) at five 5-degree quadrants of longitude and latitude ("Index Stations") along the coast from the eastern Aleutian Islands to off southern California. The time series cover from 1931 through December 1975 and are anomalies computed relative to the 1948-67 20-year reference period. Each anomaly is based on at least 12 observations of SST taken by merchant and naval vessels.

As can be seen persistent negative anomalies of SST have been present at all five coastal quadrants for the past few years. The cold period is apparently most intense and began earliest (mid 1964) in the Gulf of Alaska, later (mid 1971) in the Aleutian area and the Washington-Oregon region, and latest (mid 1973) off southern California. The negative anomalies have been very persistent in all areas, particularly in the Gulf of Alaska since mid 1970. Note also the positive SST anomalies at all 5 stations during the 1957-59 El Niño and, although many data are missing, a suggestion of the 1940-41 El Niño.

To develop a data set that is independent of ships of opportunity, I plotted anomalies of SST at coastal stations from the central Aleutians to southern California (fig. 2, 3, and 4). These data were taken by the National Ocean Survey at tide gage stations in the United States and by Environment Canada at lighthouses in British Columbia waters.

The anomalies of SST at the coastal stations are much more variable in recent years than the ship-of-opportunity data. This is to be expected since the tide gage data are taken in harbors affected by river runoff and by local heating and cooling in shallow waters. The data from Sitka, Alaska, and from British Columbia (fig. 3) are more persistently negative, possibly because the stations are more exposed to open ocean fluctuations. The data off the U.S. west coast (fig. 4) show that the cooling extended south to Neah Bay, Wash., but not at California coastal stations.

I feel that the persistent negative anomalies of SST in recent years represents a major climatic fluctuation that is observable in coastal ship-of-opportunity data but is masked in records from tide gage stations by local or distorting processes in harbors or estuaries.

The cooling also extended into the Bering Sea region but unfortunately few SST observations of long duration are available for the Bering Sea. Lacking suitable historical time series of SST, I plotted historical air temperature data for 5 selected National Weather Service stations (fig.5). These data are even more variable than the sea surface temperature data from coastal tide gage stations but do show generally negative anomalies in recent years, particularly at St. Paul Island, which is an exposed island station in the Pribilof Islands. Note the much greater variability at King Salmon, which is in a continental environment at the head of Bristol Bay, than at the maritime station Shemya in the central Aleutians. Note also the warm temperatures at St. Paul Island in 1967 and the cold temperatures since 1971. Bob Born mentioned the warm temperatures in the Aleutian Island area in 1967 and the cold temperatures in 1973.

The cold air and sea surface temperatures since 1971 were also reflected at the ocean bottom over the continental shelf in the southeastern Bering Sea. Colder bottom temperatures were observed during June of the years 1971 to 1975 than during June 1967 in the southeastern Bering Sea by the annual trawl surveys of the International Pacific Halibut Commission. Colder bottom temperatures in the summers of 1971, 1972, and 1973 relative to 1967 were also observed by the training ship *Oshoro Maru* of the Faculty of Fisheries of Hakkaido University during their annual surveys in the southeastern Bering Sea. They found that bottom temperatures of less than $+1.0^{\circ}\text{C}$ did not occur in summer 1967 but temperatures less than -1.0°C occurred in 1971, 1972, and 1973.

The negative temperature anomalies were correlated with an increase in the duration and extent of ice cover in the eastern Bering Sea. Figure 6 shows the duration and extent of ice cover in the area during the years 1967 to 1975 from information derived from satellite data. In each bar graph the duration in spring is shown for four conditions of ice cover:

- lowermost - ice in Bering Strait
- second - ice near Nunivak Island
- third - ice in Bristol Bay with open corridor
along south
- uppermost - Bristol Bay fully blocked with ice

The upper set of data for 1967-74 were developed by Dr. George Kukla of Columbia University and the lower set of data for 1974-75 were developed from weekly charts of ice and snow cover from the National Environmental Satellite Service. The two sets of data for 1974 show the difference in interpretation from the two data sources. Note that data are missing in early spring during the years 1968 to 1974 due to poor illumination. Note also that all five recent years had ice of greater extent and duration.

It is necessary to understand the causes of cold temperatures along the coast if we are ever to predict such fluctuations. At a recent symposium on Bering Sea Oceanography in Hokkaido, two Japanese scientists, Konishi and Saito, related the cold temperatures and extensive ice cover in the southeastern Bering Sea in spring of 1971 to persistence of northerly winds. To examine this factor in more detail, I computed a time series of surface meridional winds at 14 points across the North Pacific from January 1946 to May 1975. These winds are estimated from monthly mean numerical fields of surface barometric pressure from the U.S. Navy Fleet Numerical Weather Central. The winds were computed by interpolation to a 3° grid and computation of geostrophic winds. Surface winds were approximated from geostrophic winds by rotation 15° to the left and contraction by 30 percent.

Figure 7 shows the location of these points and the mean annual cycle of the computed meridional wind velocities for 1946 to 1969. The positive numbers are velocities of southerly winds while the negative numbers are velocities of northerly winds. Velocities are in decimeters per second. Southerlies occur in the eastern Gulf of Alaska year-round while northerlies occur over the western Bering Sea in all but a few months in summer. Both are related to cyclonic circulation around the Aleutian Low pressure system. Meridional winds over the eastern Bering Sea are more variable depending on the position of the Aleutian Low. Bob Born yesterday mentioned the large standard deviation of surface pressure over the Aleutian Low and its relation to east-west shifts in the position of the Aleutian Low and relation to northerly or southerly winds.

Figure 8 compares the computed winds at the 14 points for the two 2-year periods 1966-67 and 1971-72. During 1966-67 northerly winds occurred in 4 out of the 12 months over the southeastern Bering Sea (165°W) while during 1971-72 northerly winds occurred in 6 out of 12 months. Also the northerly winds were greater in magnitude during 1971-72 than during 1966-67, particularly during February.

The occurrence of southerly winds in 1966 and 1967 and northerly winds in the years since 1971 has been associated with shifts in the circulation of the upper atmosphere. Figure 9 shows the height of the 700-mb surface in the Northern Hemisphere for the warm spring of 1967. At that time there was a particularly strong ridge in the Northeast Pacific. Air from the south was advected over the Bering Sea under the western flank of this ridge. The ridge, incidentally, was the strongest such ridge over the Northeast Pacific during the spring quarter in 33 years of record.

The cold temperatures since 1971 have been related to strong ridges over the North Pacific but centered to the west of eastern Bering Sea. Northerly winds occurred under the eastern flank of such ridges. For example, in the winter of 1971-72 there was a ridge over the North Pacific that had a northward extension or lobe that extended northward across eastern Siberia to the Laptev Sea. This ridge combined with a southerly shift of the polar depression over the Canadian Arctic to drive strong northerly winds over Alaska and the eastern Bering Sea (fig. 10).

The cold weather in recent years in the southeastern Bering Sea has had various effects on the abundant fishery resources of the area. I will briefly mention effects on the Bristol Bay sockeye salmon, halibut, and fur seals.

The effects of the cold weather on sockeye salmon were felt both in the juveniles on rivers and lake systems, and also on the adults in the ocean, although information on marine effects are more sketchy. Also poorly known are the effects of high seas fishing, but the result of cold weather, high seas fishing, and possibly other factors was to reduce the U.S. Bristol Bay commercial sockeye salmon catch to very low levels. The 1974 catch in Bristol Bay was the lowest since the inception of the fisheries in the late 1800's and followed an almost equally low catch in 1973.

One effect of cold weather is to delay the return of adults returning to Bristol Bay spawning streams. The run of mature salmon returning to Bristol Bay streams was one to three weeks late in summer 1971 which caused considerable concern that the run would be much smaller than predicted. Similar delays in the run occurred in another year of cold temperatures in 1956 when migrations were delayed until waters over the continental shelf warmed to 3°C or higher.

Delays in the return of adults to the actual spawning grounds of 8 or 9 days in the cold year 1971 relative to the more normal year 1970 were found by the University of Washington Fisheries Research Institute (FRI) in the Kvichak River system.

After the adults spawn in the streams, cold weather causes the formation in winter of ice dams which cause erosion of spawning gravels and exposure or disturbance of salmon eggs deposited in them. Also cold weather in winter reduces the flow of water through the spawning gravels and consequent reduction in the supply of oxygen to the eggs. Cold temperatures also reduce the growth rates of juvenile sockeye salmon in lakes in summer due possibly to lower biological production in the lakes. Reductions in juvenile growth rates were found in summer 1971 by FRI personnel in the Kvichak River system.

After migrating downstream from the rivers, the young salmon enter Bristol Bay and begin the marine phase of their life. The young salmon do not attain significant growth during their first year at sea when water temperatures are below 4°C and thus the cold sea temperatures in 1971 retarded growth. According to Al Hartt of the Fisheries Research Institute, the 1971 seaward migrants sampled in 1972 off Adak Island were the smallest on record. Reduced growth of the 1971 seaward migrants in their first year in the ocean was also evident in the small amount of growth of the first marine zone of the fish scales sampled when the fish returned to Bristol Bay in 1973 and 1974.

Another valuable commercial fish in the southeastern Bering Sea that has been affected by recent cold weather is the halibut. Ed Best of the International Pacific Halibut Commission found that cold temperatures are related to decreased growth rates of young halibut and to changes in the distribution of 2 and 3 year old fish. Data from annual Halibut Commission surveys on a fixed station grid in the southeastern Bering Sea show that normally 2 year old halibut are a significant proportion of the catch in inshore, shallow water stations along the northern shore of the Alaskan Peninsula while 3 year

old halibut dominate the catches in Bristol Bay. Cold temperatures in 1972 appeared to inhibit the migration of halibut to these areas. In 1972 catches of 3 year old halibut at the inshore, Alaska Peninsula stations was four times the average. The cold water offshore had evidently caused the distribution of 3 year old fish to shift far enough inshore to be partially bypassed by the standardized station grid. This resulted in an underestimation of their total abundance by the survey.

Data from regular trawl surveys of the Northwest Fisheries Center suggest that year class strengths of halibut were adversely affected by cold weather. The relative abundance of 3 year olds is considered to be a good indicator of year class strengths and in 1974, the catch rates of 3 year olds (the 1971 year class) was the lowest on record for the age group since the surveys began. The 2 year olds (the 1972 year class) were present in below average numbers at both inshore and offshore stations.

A third species which seems to be affected by cold weather are fur seals. There is evidence that death rates of fur seal pups on land were higher than normal during the cold period 1951 to 1962 and particularly high during the very cold years 1954 and 1956. Mortality during 1967, the year of warmest temperatures, was particularly low suggesting that mild temperatures are associated with low mortality.

Pup mortality in the years since 1971 has been only moderate--higher than 1967 but not as high as that from 1951 to 1962. The total number of pups born in recent years is only 30% to 70% of that born during 1951 to 1962 and thus there may be some density dependent factor related to lower population size or fewer number of pups born also a factor. Highest mortalities would thus occur during years when both high population levels and cold temperatures were present.

Mortality of pups on land is less important than mortality of pups at sea after they leave St. Paul Island and before they return as young adults. Better estimates are needed of the at-sea mortality and its variability. Dr. Chapman at the University of Washington makes annual forecasts of the return of kill of 3 year old male fur seals on St. Paul Island based on multiple regression models. Dr. Chapman is including an air temperature factor as a predictor in the 1976 forecasts for the first time in recent years. The value he is using is from St. Paul Island itself which may not be representative of ocean conditions along the entire migration of fur seals from St. Paul Island to southeastern Alaska and possibly further south. Sea surface temperature data might also be preferable to air temperature data in the regression.

AVE SEA SURF TEMP
NOAA-NMFS PACIFIC ENVIRONMENTAL GROUP MONTEREY, CA

Figure 1.--1931-75 anomaly of sea surface temperature ($^{\circ}\text{C}$) from long term 1948-67 mean for 5 quadrants along the west coast of North America from the eastern Aleutian Islands to southern California.

AVE SEA SURF TEMP
NOAA-NMFS PACIFIC ENVIRONMENTAL GROUP MONTEREY, CA

Figure 2.--1931-75 anomaly of sea surface temperature ($^{\circ}\text{C}$) from long term 1948-67 mean for 5 NOS tide gage stations in Alaska.

Figure 3.--1931-75 anomaly of sea surface temperature ($^{\circ}\text{C}$) from long term 1948-67 mean for NOS tide gage station at Sitka, Alaska, and 4 lighthouses in British Columbia.

Figure 4.--1931-75 anomaly of sea surface temperature ($^{\circ}\text{C}$) from long term 1948-67 mean for 4 NOS tide gage stations in Washington and California and for Scripps Pier, La Jolla, California.

AIR TEMPERATURE
NOAA-NMFS PACIFIC ENVIRONMENTAL GROUP MONTEREY, CA

Figure 5.--1931-75 anomaly of air temperature ($^{\circ}\text{C}$) from long term 1948-67 mean for 5 National Weather Service stations in Alaska.

Figure 6.--Duration of four situations of ice cover in Eastern Bering Sea during winter and spring period 1967-75. Data for 1967-74 (upper) from Dr. George Kukla, Lamont-Doherty Geological Observatory, Columbia University, and data for 1974-75 (lower) derived from ice cover charts issued by the National Environmental Satellite Service.

Figure 7.--Upper: Location of points where meridional wind speeds were computed. The points lie along 57°N at 5° intervals of longitude from 160°E to 135°W. Lower: Monthly mean northward component of surface wind velocity by point along 57°N and month for years 1946-69. Velocities are positive for southerly winds and negative for northerly winds in decimeters per second.

Figure 8.--Monthly mean northward component of surface wind velocity by point along 57°N and month for years 1966-67 and 1971-72. Velocities are positive for southerly winds and negative for northerly winds in decimeters per second.

Figure 9.--Mean sea level pressure, height of the 700-mb surface, and departures from normal for Spring 1967 (from National Weather Service).

Figure 10.--Mean sea level pressure, height of the 700-mb surface, and departures from normal for Winter 1971-72 (from National Weather Service).

REAL TIME FISHERIES SERVICE*

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Real Time Fisheries Service is a component of the Albacore Fisheries Program at the National Marine Fisheries Service, Southwest Fisheries Center. The major goals of the program are to increase efficiency in harvesting and processing the albacore fishery resource, to maximize the recreational benefits to sportsmen, and to assist in making proper management decisions to conserve the resource. Subobjectives of the Albacore Fisheries Program are: To contribute toward the development of a strategic fishery prediction and environmental assessment service system; to provide the scientific basis for the conservation, enhancement, and optimum utilization of the North Pacific albacore fishery resource; and to contribute toward the development and operation of a tactical albacore fishery and environmental prediction and monitoring system.

Our research is divided into studies to evaluate the effects of natural environmental variations and harvesting on the resource. The results of these studies eventually will be used, together with other information, to develop simulation models interrelating the resource, the environment, and the fishery for use in forecasting the distribution, availability, and abundance of the North Pacific albacore resource.

USERS OF THE FORECAST MATERIALS

The users of the albacore fishery forecasting and monitoring services are many and varied. Strategic forecast materials are being used by:

1. The commercial albacore fishing industry, especially the fish processing and wholesaling components, and operators and owners of fishing vessels or fleets of fishing vessels,
2. the recreational fishing community, especially operators of "partyboats," and
3. the management agencies of the State and (potentially) the Federal governments.

*Extended abstract of presentation.

Tactical fishery forecasting and monitoring materials are used mainly by: The United States albacore jigfishing and baitboat fishing fleets, fish buying stations, and other components of the industry; recreational albacore fishermen; and resource managers.

NEEDS OF THE USER

The needs of the United States albacore tuna fishing and fishery managers for strategic and tactical fishery forecasting and monitoring have been specified through dialogues with members of various components of the industry and fishery scientists, and the literature. The needs of the recreational fishery interests have also been partially evaluated. A reevaluation of the needs of the user groups is required periodically because of changes in the domestic and foreign fisheries for North Pacific albacore. For example, information on fleet allocation no doubt will have to be added to the strategic list of needs of the U.S. industry in the near future.

The strategic needs of all user groups are on time scales of forthcoming season and up to several seasons, and on an ocean-area space scale. Strategic information is needed on:

1. The general area in which the albacore stock will be available in the forthcoming season relative to its area of long-term availability, specifically, the seasonal geographic location of centers of the fishery, e.g., north-south and nearshore-offshore;
2. the range of the fishery in time and space;
3. the probable level of abundance of the albacore stock over the fishery area in the forthcoming season, relative to its long-term abundance;
4. variation in expected size composition of the fish;
5. the probable long-term oceanographic conditions which may affect fishing operations, such as the occurrence of broad-scale anomalies, and specifically information on general ocean surface and subsurface temperature conditions; and
6. the probable long-term wind and sea conditions and predicted climatic anomalies which may affect broad area fishing operations.

CHANGES IN USER NEEDS

The changes in the character and amount of harvest of the U.S. and foreign fisheries for North Pacific albacore point toward the need in the near future for management of the resource at all levels including the international. An effective albacore fishery forecasting and monitoring system could play a significant role in the development of a real-time management system for the North Pacific albacore resource. It appears that there will be an increased

need for albacore prediction and monitoring on the part of resource management agencies in the not-too-distant future.

Because of increased costs and other factors, there appears to be a greater attempt than usual on the part of the albacore tuna industry to increase return on capital investment to maintain or increase profits. This is taking many forms (e.g., price increases to consumer) depending on the segment of the industry involved. The fisherman can increase the return on his capital investment to maintain or increase his profit margin by catching a larger amount of fish at the same level of efficiency as in the past, catching the same amount or less fish in a more efficient manner (e.g., reduce search time), obtaining an increase in price paid for fish, or by combining any of these procedures.

Since the benefits of fishery forecasting and monitoring to the industry can include a reduction in search time and a stabilization of landings, it appears there will be an increased need by industry for these services.

The remainder of the presentation included reviews of:

1. The general description of the life history of albacore;
2. the description of the albacore fisheries by space, time, and landings, with emphasis on the U.S. fishery;
3. the results of cooperative research conducted jointly with the U.S. albacore fishing industry on the influence of marine environmental features on the distribution of albacore, large-scale and small-scale migration patterns, and age and growth of albacore;
4. the cooperative work with Japanese on population assessment and impact of harvesting on albacore; and
5. the system for distributing the following forecast and advisory information to users: seasonal forecasts, bi-weekly narrative albacore fish bulletins, daily broadcasts of albacore fishing and environmental information over marine radio bands, monthly and bi-weekly sea surface temperature charts, and weekly sea surface temperature charts transmitted via radio facsimile.

DIVISION OF FISHERIES RESOURCE ASSESSMENT
TASK: FISHERY ANALYSIS: SHRIMP, NORTHERN GULF OF MEXICO

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The shrimp fisheries collectively have been the most valuable commercially in the United States for about the last 20 years. The value of these fisheries, including domestic shrimp sales, exports, and allied activities, exceeds \$1 billion annually. Approximately 70% of the domestic production of shrimp comes from the southeast region (Gulf and South Atlantic States). In 1974 shrimp production from this region was 134 million pounds (heads-off) with an exvessel value of \$155 million. About 90% of the domestic shrimp production of this region comes from the Gulf States area.

The Gulf Shrimp Fishery is not under management within a State-Federal program, but the individual Gulf States regulate shrimp fishing. Economic overfishing is taking place, but there is insufficient evidence to determine whether or not biological overfishing also is taking place. For these reasons, research is being conducted, within the Task, on the following objectives:

1. To develop mathematical models capable of explaining and predicting variations in yield from shrimp fishery resources of the Gulf of Mexico.
2. To use outputs from these models as guides to choose among various shrimp fishery management alternatives.

The approach involves acquisition, assembly, and analysis of comprehensive data banks on (a) catch and fishing effort statistics, (b) environmental data, (c) habitat alteration data, and (d) socio-economic data. These data will provide an information pool on which to base the mathematical model or models. Data input is derived from other NMFS Tasks and other Federal and State agencies and institutions. The major benefit will be an information base to support decisions concerning management of Gulf of Mexico shrimp fisheries, to meet present needs and those arising from extended jurisdiction.

(The modeling concept of 1 above is discussed more fully in "Gulf of Mexico Shrimp Resource Research," by Caillouet and Kenneth N. Baxter, Marine Fisheries Review, 35, (3-4), 21-24, 1973. The authors' abstract states, "This paper describes shrimp resource research presently being conducted by the Galveston Laboratory of the National Marine Fisheries Service Gulf Coastal Fisheries Center. Discussed are plans for development of a mathematical model capable of explaining and predicting changes in shrimp catch, and ongoing mark-recapture experiments, prediction of catch, stock identification studies, and

study of spawning grounds. Trends in Texas and Louisiana brown and white shrimp catches and catch rates are presented.")

Near the beginning of these workshop sessions, Dr. McQuigg stressed the need for continuous monitoring in an operational system for predicting field crop yields. I have been at the Galveston Facility for almost four years, but my interest in seasonal and annual fluctuations began in 1964, when I directed a research program involving monitoring of abundance and distribution of postlarval commercial shrimp (*Penaeus* spp.) in Vermilion Bay, Louisiana. One of the objectives of this program was to predict local shrimping success from abundance indices of postlarval shrimp. The study was supported by contract with the Bureau of Commercial Fisheries Laboratory in Galveston.

It is obvious that shrimp abundance and distribution are dependent to a large extent upon environmental variables. Because shrimp are short-lived, response time to environmental change is likewise short. To me, it represents a data-rich, more or less ideal, fisheries system for studying effects of environmental driving forces. Shrimp (detritus feeders) are just one step above primary productivity on the trophic chain. It is a relatively unstable population system with biological success strongly dependent upon tremendous biotic potential: One ripe female shrimp carries about $\frac{1}{4}$ million ripe eggs (probably many more in the undeveloped stage), and she may spawn more than once per year. Spawning is more or less year round in the shrimp population, with peaks in fall and spring coinciding with peak phytoplankton blooms and transition periods (and overturns) of current patterns.

Institutional constraints inhibited progress in shrimp modeling the first few years, but in 1973 a series of crises hit the shrimping industry in the Gulf. A poor shrimp crop related to a cold winter and flood conditions, coupled with increased fuel costs of the energy crisis, increased costs of equipment, consumer resistance, and stockpiles of shrimp in frozen storage, combined to work considerable hardship on the harvesting sector of the industry. Further impetus for shrimp modeling work has been provided recently by Mexican-U.S. talks concerning extended jurisdiction. I am pleased that one of the results is renewed emphasis on shrimp fishery analysis.

Until 1976, the research program concentrated on (1) small-scale monitoring activities (postlarval and juvenile shrimp) in the Galveston Bay area, (2) assembly of time-series files of biological, fisheries statistics, and environmental data, (3) stock identification studies, and (4) preliminary analyses of biological and fisheries statistical data. In FY 76, the staff was cut to 8 personnel, including the Division Chief, Secretary, Task Leader (Fishery Biologist), Operations Research Analyst, Computer Programmer/Data Manager, Statistician, and two additional Fishery Biologists. This group has the objective of applying their analytical expertise as a team to fishery analysis and modeling activities concerning Gulf shrimp fisheries.

In closing, we are now at a point where much of the data needed for our assessments is in a form amenable to computer analysis. I am enthusiastic about the possibility that our staff might obtain assistance from CCEA in modeling activities relating environment to shrimp yield. We also are

attempting to acquire access to computing capability sufficient to the task, because those used to assemble our data banks and to conduct preliminary analyses have proven insufficient to accommodate our present needs.

LARVAL TRANSPORT AND YEAR-CLASS STRENGTH
OF ATLANTIC MENHADEN*

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This paper represents an attempt to determine the influence of environmental factors on year-class strength of Atlantic menhaden (*Brevoortia tyrannus*). Since year-class size is a function of the size of the spawning stock and of the effects of the environment, it was necessary to determine both the density-dependent and the density-independent relationships to weigh the relative influence of each. The understanding of the resource-environment relationship is necessary to predict year-class size both for conservation and for utilization of the Atlantic menhaden resource.

Menhaden spawn along most of the U.S. east coast, primarily north of Cape Hatteras in the summer and fall, and south of Cape Hatteras in the winter. Most spawning, particularly south of Cape Hatteras, occurs well offshore. The species is estuarine dependent, and larvae enter estuaries at a size of 18 to 22 mm after an offshore phase lasting 1.5 to 2 months.

A mechanism for the transport of larvae from offshore spawning areas to inshore nursery grounds during the passive drift phase would increase the survival rate of Atlantic menhaden. Variations from year to year would result in variations in year-class strength. Theoretical wind-driven water mass movement (Ekman transport) was reviewed for its potential as a transport mechanism. Net water movement was found to be onshore during winter months both north and south of Cape Hatteras and also to vary extensively from year to year. Peak periods of onshore transport coincided well with periods of menhaden spawning activities.

An intensive larval sampling program was carried out in Onslow Bay, N.C., from October 1972, through April 1974. The survey was made to determine the timing of spawning in Onslow Bay, the distribution and abundance of larvae as related to oceanographic conditions, and the relationship between oceanographic and biological findings and theoretical Ekman transport. Larvae were taken as early as November, but were not abundant until January. Distinct larval modes found throughout the winter of 1972-73 indicated that spawning occurred in waves, and the growth rate of separate batches of larvae appeared to be traceable. Larval abundance decreased in March as spawning ended and larvae

*Expanded abstract of a paper presented at CCEA/NMFS workshop. Portions of the paper are in press as: Nelson, Walter R., Merton C. Ingham, and William E. Schaaf. Larval transport and year-class strength of Atlantic menhaden. U.S. National Marine Fisheries Service Fishery Bulletin, Jan. 1977.

moved into estuarine nursery areas. Differences in distribution and abundance during the winters appeared related to different oceanographic conditions. During the first winter, massive intrusions of colder, low salinity water entered Onslow Bay from the north, carrying larvae spawned north of Cape Lookout.

During the second winter, oceanic water was found in Onslow Bay and there was strong evidence of water mass movement offshore. Circulation patterns during the two winters corresponded with expected circulation determined from atmospheric pressure gradients which generate wind-driven circulation. A real relationship between theoretical Ekman transport and larval movement was apparent, supporting the hypothesis that Ekman transport acts to carry larvae from offshore spawning grounds to inshore nursery areas.

A density-dependent Ricker function was derived for Atlantic menhaden and used as a basis for determining the density-independent environment influence. The yearly observed number of fish recruited at age 1 was divided by the number of fish estimated from the spawner-recruit curve to determine the survival index for each year class from 1955-70. An index greater than 1.0 indicated higher than expected survival and was attributed to environmental factors conducive to such survival. The total number of eggs produced by the spawning stock was used as an indicator of spawning stock size to account for differences in growth and fecundity of spawning adults attributable to different population densities between years. The spawner recruit model indicated that a stock size of approximately 530 million adults, ages 3 and over, is optimum for producing the greatest number of recruits. Optimum egg production is approximately 60×10^{12} eggs which produces, on the average, 3.68 billion fish at age 1.

Individual regressions of the survival index on the various environmental factors were run. Zonal Ekman transport at 35°N, 75°W accounted for over 62% of the variance between actual and expected recruitment for Atlantic menhaden and had a correlation coefficient of 0.789 with the survival index. Another transport index at 33°N, 78°W also was highly significant, leading to the conclusion that transport south of Cape Hatteras is a major factor in the formation of year-class size. Transport north of Cape Hatteras in the Middle Atlantic Bight at 39°N, 75°W was also significant through the late fall and winter, indicating the process is important along most of the menhaden spawning range. Regressions of the survival index on Chesapeake Bay discharge and on mid-Atlantic bight minimum temperature were not significant, probably because local effects were obscured by survival throughout the spawning range and because of the masking effect of north winds associated with cold air masses that generate onshore transport.

All factors were combined to develop a multiple-regression recruit-environment model and a predictive equation for the survival index. The environmental factors incorporated in the model yielded a cumulative correlation coefficient of 0.919 and accounted for over 84% of the variance in the survival index from the density-dependent Ricker function. The model satisfactorily described the size of a year-class in 14 of the 16 years used in the analysis.

A range of recruitment levels, based on years of high and low transport, was developed for Atlantic menhaden and indicates that a wide range in numbers of recruits can be expected under similar stock sizes at various transport rates. A chronological representation of the spawner-recruit relationship for Atlantic menhaden shows three different regimes in the 1955-70 period. Stock size was high in the late 1950's and usually exceeded that necessary to produce the maximum number of recruits. Heavy fishing pressure and poor survival resulted in a period of decline in stock size from 1961-66. The stocks then restabilized around a small stock level that is too low to allow large-scale response to favorable environmental conditions. A similar situation occurred in the Pacific sardine fishery shortly before it collapsed; the same collapse could occur in the Atlantic fishery as a result of several years of unfavorable environmental conditions and continued heavy pressure from the fishery. There are several biological differences, however, between Atlantic menhaden and Pacific sardine that make the Atlantic menhaden stock less likely to suffer a complete collapse.

The estimated maximum sustainable yield for the period of study for Atlantic menhaden was approximately 419,000 metric tons, assuming natural mortality and fishing rates of 0.42 and 0.36 respectively, spread over ages 1 through 6. The fishery took approximately the same average catch, but did it by overfishing in the late 1950's; thus the low catches in recent years. The fishery caught menhaden at a small average size, when the yield per recruit was low. A management scheme, based on the number of recruits predicted from the recruit-environment model, resulted in a small error from the calculated maximum sustainable yield but would have maintained adequate spawning stock size and a broad age structure in the fishery. With controlled effort, to allow spawning stock size to reach an optimum, the fishery should have been able to increase its catch by over 230,000 metric tons per year in recent years.

Based on the determination of the density-dependent and density-independent stock and recruitment functions for Atlantic menhaden, basic conclusions are: in years of poor environmental conditions recruitment is low regardless of stock size; extremely low spawning stock sizes in years of poor environmental conditions result in recruitment below the level needed to maintain the fishery; favorable environmental years will produce exceptional year classes and a proportionally greater harvestable surplus at stock sizes near the spawning optimum; and a series of poor environmental years, coupled with excessive fishing pressure, will reduce stock size to a level which produces little harvestable surplus.

GULF STREAM MEANDERS AND WARM CORE EDDIES--IRREGULARLY
OCCURRING INFLUENCES ON THE FISHING GROUNDS

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North of Cape Hatteras, the large Gulf Stream meanders and warm core eddies ("rings") that occur at irregular intervals of time along the left (shoreward) side of the stream apparently cause the strongest subsurface currents and non-seasonal (aperiodic) variations in water mass properties found in the slope water region adjacent to the outer continental shelf. Although meanders and eddies occur on both sides of the stream, it is only those on the left that sometimes move into the proximity of the fishing grounds of the continental shelf and slope off New England and the Middle Atlantic States. The meanders and eddies are both a common occurrence in this region (about 6 warm core eddies per year during 1974 and 1975 (Bisagni 1976)), but their influence on the fishing grounds is quite variable because they characteristically remain in deep water, with apparently little direct effect on environmental conditions in the waters of the continental shelf and slope. The infrequent meander or eddy, however, which moves close along the continental slope can have considerable effect on these waters (Iselin 1939, Chamberlin 1976). (See figures 1 and 2.) Furthermore, large eddies that remain in deep water apparently can have significant effects by offshore entrainment of shelf water (fig. 3 and 4).

There are two principal ways to monitor the movements and environmental effects of meanders and eddies: by utilizing interpretations of infrared-radiometer imagery from NOAA satellites to observe the locations, movements, size, and other characteristics of meanders and eddies as they appear at the sea surface, and by obtaining direct observations of these features from vessel cruises. Interpretations of the satellite imagery and copies of some of the imagery, itself, are obtained through the cooperation of oceanographers of the U. S. Naval Oceanographic Office (fig. 3) and the NOAA National Environmental Satellite Service (fig. 4). Because the meanders and eddies change position slowly--usually no more than a few miles per day-- the weekly interpretations produced are a more than satisfactory basis for monitoring, despite the fact that cloudy weather obscures the satellite imagery a large part of the time.

Shipboard observations are needed intermittently, rather than on a regular schedule such as that of the satellite interpretations. These observations become essential only when satellite imagery indicates that a particular eddy or meander is having, or soon will have, a significant effect on the fishing grounds. Because satellites reveal only the sea-surface temperature character of meanders and eddies, the depths and boundary slopes of these features can be reliably determined only from shipboard observations; to some degree instrument drops from low flying aircraft are also useful.

Satellites often give an inaccurate measure of both the size and location of meanders and eddies when these features are overridden at the surface by surrounding waters or chilled at the surface by cold winds. Eddies sometimes seem to disappear entirely in the satellite imagery for days and perhaps weeks and then often reappear many miles from where last seen. Following prolonged periods of cloudy weather, the relocation of an eddy may be difficult. A large shallow patch of Gulf Stream water that has overridden the slope water can easily be mistaken for the eddy.

Adequate measurement of the effects of meanders and eddies on the fishing grounds is probably feasible at present only with combined observations from ships and satellites. Shipboard observations are paramount in revealing effects such as upwelling adjacent to meanders or eddies, subsurface injection of warm Gulf Stream or eddy water onto the shelf, and subsurface entrainment of shelf water. Combined observations should be particularly advantageous for measuring the volume of surface entrainment of shelf water. The areal extent of entrainment can be estimated from satellite imagery, and the depth of the entrainment layer from shipboard.

Making observations in meanders and eddies will be a continuing difficult management problem, because these oceanographic phenomena are at present unpredictable as to their magnitudes, places of origin, and speeds and directions of travel, whereas vessel cruises are ordinarily planned well in advance of operations.

Formation and Characteristics of Warm Core Eddies

Warm core eddies form in the slope water region off the continental shelf by detachment of meanders on the left side of the Gulf Stream. The detached meander maintains continuity of flow by closing into a "ring" at the area of detachment. The rotational flow, in a clock-wise (anticyclonic) direction, continues by inertia, at speeds from as low as 0.6 to 1.0 knots (30 to 50 cm/sec) (Saunders 1971) to more than 1.8 knots (90 cm/sec) (Thompson and Gotthardt 1971). The eddies have a warm core because they enclose Sargasso water that has crossed the Gulf Stream within the originating meander. (Eddies also form from meanders on the right side of the Stream. These eddies, which move off into the

warm Sargasso Sea, rotate counterclockwise and contain a cold core of slope water). The warm core eddies seen off New England mostly form in the slope water region southeast of Georges Bank, where meandering of the Gulf Stream becomes extensive.

Unlike Gulf Stream meanders, which move slowly eastward like waves, warm core eddies typically move west and southwest in the slope water region at varying rates up to about 0.2 knots (10 cm/sec), but often halt or move in irregular directions for periods of days or even a few months (Bisagni 1976, Chamberlin 1976). Some eddies recontact the Gulf Stream soon after their formation and are resorbed. However, those which continue to move to the west and southwest may continue to exist for over 6 months, but are eventually trapped and resorbed by the Gulf Stream at about the latitude of Virginia, where the stream runs close to the continental slope. Bisagni (1976) found that the warm core eddies were present about one-fifth of the time off the New York Bight during 1974-75.

Effects of Meanders and Eddies on the Fishing Grounds of the Continental Shelf and Slope

Direct effects of Gulf Stream meanders and warm core eddies on the environmental variability on the fishing grounds have probably been reasonably well observed, but the influence of this variability on the fishery resources is largely conjectural. Five kinds of environmental effects and their possible influences on the fishery resources and on fishing can be identified:

1. Warming of the upper continental slope and outer shelf by direct contact of a meander or eddy (fig. 1). This may influence the timing of seasonal migrations of fish as well as the timing and location of their spawning.

2. Injection of warm saline water into the colder less saline waters of the shelf by turbulent mixing at the inshore boundary of a meander or eddy (fig. 2). This may have influences on the fishery resource similar to that of direct warming, and also may cause mortality of fish eggs and larvae on the shelf when the cold water in which they live is warmed beyond their tolerance by the mixing-in of warm slope water.

3. Entrainment of shelf water off the shelf--an effect that is frequently seen in satellite imagery (fig. 3 and 4). Mortality of Georges Bank fish larvae is known to occur, presumably because of temperature elevation, when shelf water in which they occur is carried into the slope water (Colton 1959). The most profound effects of the entrainment on the fishing grounds may be changes in circulation and water masses resulting from the replacement of the waters lost from the shelf.

4. Upwelling along the continental slope, which may result in nutrient enrichment near the surface and increased primary biological productivity.

5. Strong currents on the outer shelf and upper slope. Prolonged submergence of the surface floats of lobster pots and even losses of gear are possible results that warrant investigation.

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Figure 1.--Vertical temperature section showing a warm core eddy contacting the outer continental shelf and upper slope near the Hudson Canyon on May 19, 1974 (from Applications Research Division, NavOceanO, 1974).

Figure 2.--Vertical temperature section showing injection of warm core eddy water onto the continental shelf south of New England on March 28-29, 1974. Only the inshore margin of the eddy appears in the section (after Chamberlin 1976).

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