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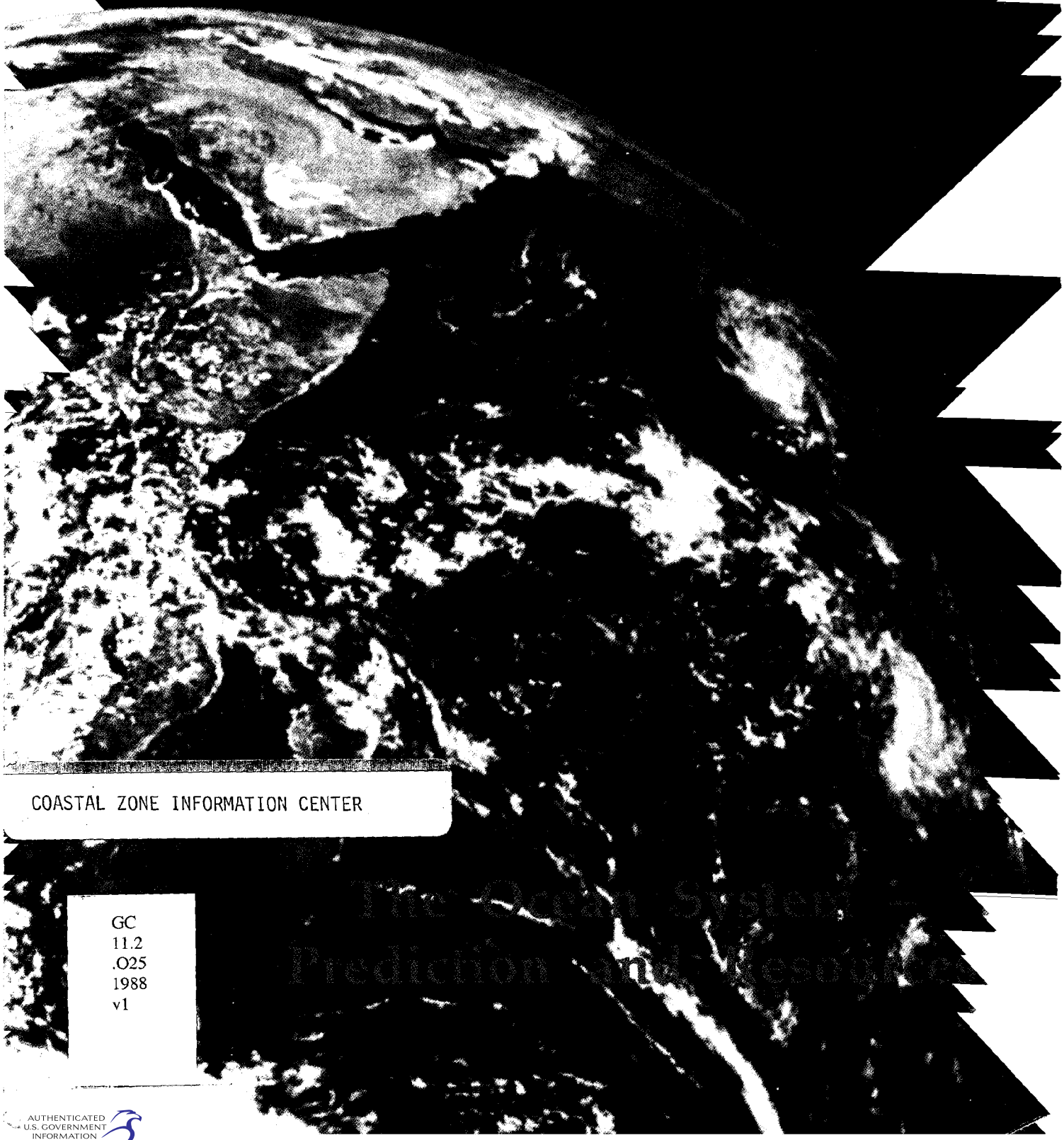

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The Ocean System Prediction and Resources

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OCEAN SYSTEM STUDIES
NOAA/OAR
RESEARCH STRATEGY I

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The Ocean System – Prediction and Resources

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Ocean System Studies
NOAA/OAR Research Strategy I

The Ocean System – Prediction and Resources

Produced by the

University Corporation for Atmospheric Research

based on a series of

NOAA Symposia and Meetings

Boulder, Colorado

December 1988

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Foreword

The responsibility of the Office of Oceanic and Atmospheric Research (OAR) is to formulate and execute purposeful, comprehensive research programs that provide technological and scientific principles on which to base improvements of NOAA's services and products. As such, OAR must look ahead to opportunities that will enhance the Nation's strength and provide the knowledge base upon which to wisely pursue these opportunities. It must also provide early warnings of problems our Nation will face and the knowledge upon which cost-effective solutions can be based. Accordingly, OAR must offer continuity that transcends the changing political climate because many of the research programs require time scales of longer duration than that of the political process. At the same time, it cannot be isolated from changes in priorities that are communicated by our Nation's people through the political process. To accomplish this, an effective dialogue is required.

It is in the above context that I am initiating an episodic series of publications on contemporary issues that OAR is addressing in concert with other NOAA elements, starting with the following subjects that are addressed in this report:

Ocean Circulation and Global Climate Change
Ridgeflux: Hydrothermal Venting on a Global Scale
Fisheries Oceanography
Sea Ice and Arctic Ecosystems
Estuarine Systems
Marine Chemistry, Biology and Climate

Future reports will address other issues.

The purpose of these reports is to communicate to others OAR's view of opportunities for NOAA in critical areas of research for which we have a responsibility. It is my hope that the statements will stimulate comments from a varied audience, and that the research community can use them to identify opportunities for cooperation with NOAA.

Joseph O Fletcher

Joseph O. Fletcher
Assistant Administrator
Oceanic and Atmospheric Research
NOAA

Editors' Preface

Ocean System Studies I: Prediction and Resources is the first of an episodic series of reports identifying NOAA/OAR research opportunities and strategies. The contents address a number of issues global in scope and vital to mankind. The problems are greater in magnitude than any one nation's capability to attack them. Given the wide nature of NOAA's charter, this document articulates salient research areas where NOAA can make a unique contribution, and where public and private issues intersect NOAA's research capability.

As a strategic statement, this document highlights the issues to which OAR is committed in the broad categories listed in the Table of Contents. It reflects the direction we want to go, regardless of the vicissitudes of the budget process. The modulation of the effort may change but not the direction. It is not an exclusive commitment to these areas of research at the expense of others. Rather than paint an entire landscape, this document settles on a handful of high points on the research horizon at this time.

The papers cover a diverse set of research agendas, research methods and goals. In order to provide a semblance of organization, each chapter is preceded by an abstract summarizing the research problems and opportunity, the essential elements of the research strategy, the question of timeliness (the "Why now?" question), NOAA's role, and the benefits to be derived from investment in the research. The text of each chapter reflects the style of a number of different work groups. You may expect divergences in style, tone and approach. Rather than force uniform consistency and editorial prerogative, we have simply tried to insure that each paper provides necessary background information on the scientific issue and the sense of urgency surrounding the research, details of the research questions and strategy to address it, and coordination with other agencies or universities in developing NOAA's unique contribution.

The papers are statements of strategy and are not meant to be budget initiatives or program implementation plans. They focus on strategic research needed to answer pressing scientific problems for resource management and for an understanding of the global environment.

In most cases, the research statements are the result of a series of working groups and/or workshops on the topic. They usually involve the input of NOAA line organizations, other agencies and universities. The following individuals participated in the development of these papers:

I. Ocean Circulation and Global Climate Change

Based on Global Climate Change Workshop report written by Robert Molinari, AOML, using written contributions or private communications from Kirk Bryan, GFDL; John Diamante, OCAR; J. O. Fletcher, OAR; Richard Gammon, PMEL; Dave Goodrich, OCAR; J. Mike Hall, OCAR; Don Hansen, AOML; Ed Harrison, PMEL; Stan Hayes, PMEL; Joe Huang, OCAR; Richard Legeckis, NESDIS; Ken Mooney, OCAR; George Philander, GFDL; Ed Sarachik, University of Washington; Jorge Sarmiento, Princeton University; Uwe Radok, CIRES; William Woodward, NOS.

Drawn from current research of: Kirk Bryan, S. Manabe, M.J. Spelman, R.J. Stouffer–GFDL.

II. Ridgeflux

Eddie Bernard, PMEL; Steve Hammond, PMEL; Dick Feely, PMEL; Ed Baker, PMEL; Bob Embley, PMEL; Chris Fox, PMEL; Gary Massoth, PMEL; Peter

Rona, AOML; Terry Nelsen, AOML; Steve Piotrowicz, AOML; Dave Duane, NURP; Bill Lavelle, PMEL; Glenn Cannon, PMEL.

III. Fisheries Oceanography

Gene Fritz, National Sea Grant Office; Jim Schumaker, PMEL; Peter Ortner, PMEL; Tom Fontaine, GLERL; Kenneth Sherman, NMFS; Donald Hoss, NMFS; Gary Stauffer, NMFS; Reuben Lasker, NMFS; Robert Francis, University of Washington; Larry Crowder, North Carolina State University; James Kitchell, University of Wisconsin.

IV. Sea Ice and Arctic Ecosystems

Jim Overland, PMEL; Carol Pease, PMEL; Knut Aagaard, PMEL; Roger Barry, CIRES/ University of Colorado; Don Cavalieri, Goddard Space Flight Center; Gary Wall, Navy/NOAA Joint Ice Center; Norbert Untersteiner, University of Washington; Vera Alexander, University of Alaska.

V. Estuarine Systems

Brian Edie, GLERL; Larry Swanson, SUNY/Stonybrook; Garry Mayer, National Sea Grant Office; Don Atwood, AOML; Herb Curl, PMEL.

Based on Coastal Marine Research Plan PDP, Larry Swanson, SUNY/Stonybrook; Garry Mayer, National Sea Grant Office; Harold Stanford, NOS; Bud Cross, NMFS; Jim Thomas, NMFS.

VI. Marine Chemistry, Biology and Climate

Written by: Bill Graham, National Sea Grant Office.

Drawn from research by: Steve Piotrowicz, AOML; George Harvey, AOML; Peter Ortner, AOML; Tim Bates, PMEL; Richard Gammon, PMEL.

Using material produced or provided by: Don Atwood, AOML; Alex Pszemny, AOML; Steve Piotrowicz, AOML; Tim Bates, PMEL; Richard Gammon, PMEL

AOML: Atlantic Oceanographic and Meteorological Laboratory OAR/NOAA.

CIRES: Cooperative Institute for Research in Environmental Science, OAR/NOAA.

GFDL: Geophysical Fluid Dynamics Laboratory, OAR/NOAA.

GLERL: Great Lakes Environmental Research Laboratory, OAR/NOAA.

NESDIS: National Environmental Satellite & Data Information Service, NOAA.

NMFS: National Marine Fisheries Service, NOAA.

NOAA: National Oceanic and Atmospheric Administration.

NOS: National Ocean Service, NOAA.

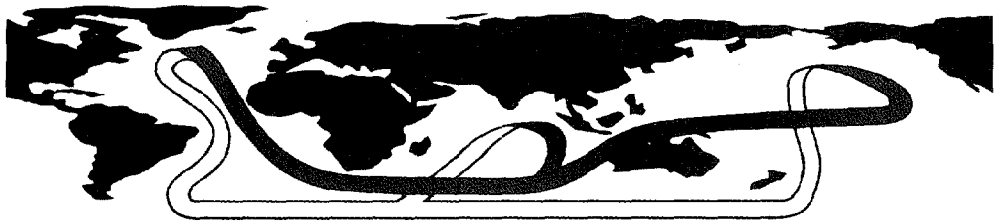
NURP: National Undersea Research Program, OAR/NOAA.

OAR: Office of Oceanic and Atmospheric Research, NOAA.

OCAR: Office of Climatic and Atmospheric Research, OAR/NOAA.

PMEL: Pacific Marine Environmental Laboratory, OAR/NOAA.

SUNY: State University of New York.



Chapter I

Ocean Circulation and Global Climate Change

Executive Summary

Problem and Opportunity

For several years concern has been mounting that the earth's global environment may be changing in ways to which we can not easily adjust. The long-term trend in atmospheric carbon dioxide and the known radiative effects of this and other trace gases, and recent data suggesting significant changes in the earth's ozone layer are evidence of the potential for major changes in the global climate.

It is clear that man is no longer a passive participant in the global environment. Human activity has reached the scale where it affects the global environment in ways that we do not fully understand. The effects of this activity, coupled with the natural variability in the global climate system, will have profound implications for the future. Current and anticipated changes in the global environment will produce significant economic, social and political problems which this Nation, in cooperation with other nations, must be prepared to address.

NOAA has the responsibility to understand and ultimately forecast interannual, decadal and longer term climate change. On these time scales, the transport, storage and exchange of heat by the surface and subsurface waters of the world oceans, and the mass, momentum and energy exchanges between the oceans and the atmosphere, are of crucial importance in influencing climate change.

Research Strategy

The climate system can be characterized as a global heat engine having two working fluids (the oceans and atmosphere) that transports heat mainly from the equatorial/tropical zone to the polar regions. The research goal is to be able to understand and predict the behavior (climate) of the system on different time scales.

The research strategy is directed at resolving the critical questions that must be answered in order to achieve the goal. First, the behavior of the system that needs to be understood is defined from current observations and reconstructions of its past behavior. Then, understanding is derived from diagnostic studies of the observations and through numerical simulations of the response of the coupled atmosphere and oceans. Answers to critical questions provided by focused research serve to refine both understanding of the system and the simulation models. Refined models ultimately provide the basis for predictions of the future behavior of the system.

Three broad tasks must be addressed. These are: ocean circulation models must be refined and verified; observational systems must be designed and deployed for ocean climate monitoring; and new in situ *technology for ocean monitoring must be developed.*

The top level questions about the global heat engine that need to be answered are:

- *what is the heat transport of the oceans (how much and from where to where)?*
- *how is the transport performed (what water masses are involved and how is the system forced)?*

- *what is the temporal and spatial variability of the behavior?*
- *how do changing ocean conditions influence the atmosphere and what ocean features are most important in this respect?*

These questions lead to increasingly more specific questions which the research strategy must address.

A specific research question of importance in interannual climate variability concerns the effect on the phenomena associated with El Nino and the Southern Oscilation (ENSO) of water mass exchanges between the Indian and Pacific Oceans. On interdecadal and longer time scales, some important research questions concern:

- *the role of North Atlantic deep water formation, and exchanges with the northern branches of the subtropical gyre, in regulating the thermohaline circulation, and*
- *the identification of feedback control mechanisms in the Atlantic thermohaline circulation and their role in possible major, and relatively sudden, climate changes taking place on the century time scale.*

On both interannual and interdecadal time scales, some important research questions relate to:

- *understanding the dynamics of the ocean/atmosphere fluxes of heat, moisture and momentum, particularly with respect to areas controlling the time-variability of water mass formation,*
- *the relationship of changes of heat content of the equatorial zones and changes in the position of the Intertropical Convergence Zone (ITCZ) and their relationship to climate variability in higher latitudes, particularly in the Atlantic basin.*

Why Now?

The world oceans play a central role in climate change, and the problems presented by global climate change are very real. Recent scientific advances and planned technological improvements (e.g., supercomputers and satellite systems) now make it possible to take a truly global look at the earth, including the world oceans, as a system and engage, for the first time, in a national (and international) scientific program to understand and predict changes (both natural and man-made) in the global environment.

Benefits

The earth may face climate and environmental changes on time scales of importance to living generations, their civilizations, and future progeny. These changes may be due to natural variability, or may be human-induced, such as the effects of increasing CO_2 levels and changes in ozone levels. Regardless of the source of change, the ability of scientists to predict the direction and magnitude of change will allow nations and international institutions to be better prepared to accommodate to these changes, or to otherwise mitigate their consequences. The research strategy laid out for ocean circulation is directed toward providing forecasters and modelers with refined ocean models having predictive capability commensurate with the existing atmospheric models and to support development of coupled models of the two fluid systems.

1.0 Introduction

In their last conversation, Alice B. Toklas asked Gertrude Stein, "What are the answers, Gertie?" Gertrude Stein's reply was, "But, what are the questions, Alice?"

Research is directed toward a goal, most often posed in terms of a question, or questions, to be answered. In particular, there is usually a logical sequence, or hierarchal order, of questions leading to the goal or purpose. The most general question at the top of the hierarchy must set the proper direction for a research strategy designed to achieve the goal. Therefore, the first order of business in formulating a well focused ocean climate research strategy is to properly pose the sequence of questions that needs to be answered.

1.1 The Climate System as a Global Heat Engine: The Conceptual Framework for Developing a Research Strategy

The traditional definition of climate is the long-term behavior of the atmosphere, described in terms of averages of the basic parameters that characterize the weather, such as temperature, pressure, wind velocity, and precipitation. Climate is then distinct from the climate system, which consists of those elements of the earth system that determine climate.

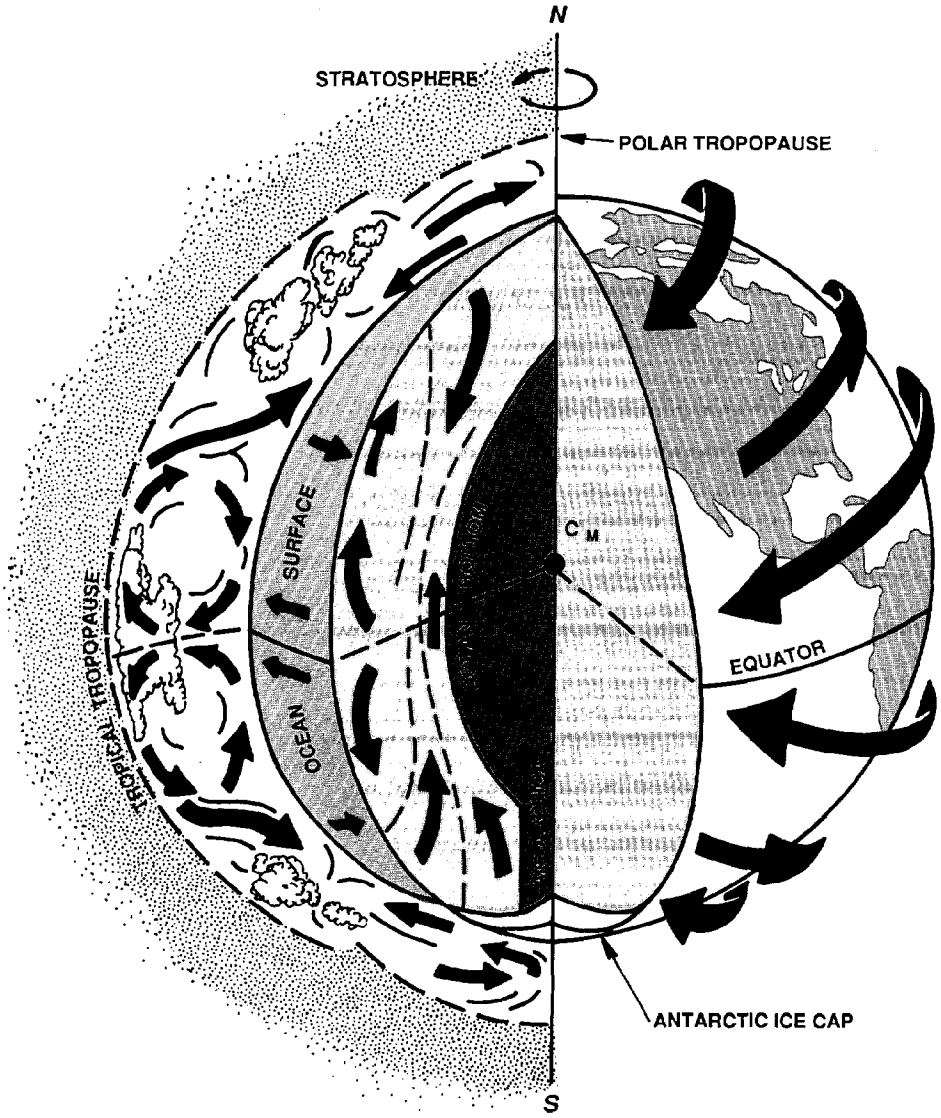
These are, at a minimum, the total atmosphere, the oceans, the land surface and the cryosphere (Figure 1). If our ultimate goal is prediction on climate time scales, then we must concern ourselves with simulating and predicting the interactive processes of the climate system.

The essential nature of the climate system illustrated in Figure 1 is a "global heat engine" involving two principal working fluids, the atmosphere and oceans. The oceans and the atmosphere redistribute heat between the "sources" and the "sinks." The major source areas are located mainly in the equatorial and tropical regions, while the major sinks are located principally in polar areas. This description of the climate system provides a self-consistent metaphor for formulating critical questions and a research strategy to answer them. In order to predict changes in climate, we need to answer the question:

- What is the temporal and spatial variability of the forcing fields driving the two working fluids of the global heat engine and what is the variability of the response of these fluids in space and time?

This constitutes the most general question which the research strategy must address.

Figure 1: The Climate System as a Heat Engine. The dynamic and thermodynamic coupling of the earth's atmosphere, oceans, cryosphere and land surface provide the global heat transport of the climate system.



The ultimate driving forces of the climate system's heat engine are the incoming solar radiation, the outward radiation flux (the reflected albedo field and planetary radiation), the gravitational and rotational (Coriolis) forces. In terms of the oceans, the main fields associated with the forcing of oceanic component of the heat engine act at the interface between the oceans and the atmosphere. These fields are the distribution of wind stresses, the fluxes of sensible and latent heat, and mass fluxes. The mass and latent heat fluxes are mainly concerned with moisture transport at the ocean surface. The heat flux also is closely related to sea surface temperature (SST) distributions. The main fields associated with the forcing of the atmosphere are the same surface fluxes and SST field, but the corresponding quantities for the land and cryosphere surfaces also are involved in driving the atmospheric circulation. Hence, defining and understanding the spatial and temporal variability of these ocean surface fields must be an important concern of the research strategy.

Starting with the general question above, a logical sequence of questions for ocean climate research follows with:

- What quantity of heat is transported by the global oceans and how is that transport distributed globally?
- How are the different oceanic water masses involved in the specifics of the global heat transport?
- What is the temporal variability of the oceanic heat transport?

At the same level of generality, the next questions relate the role of the oceans back to the atmosphere in the overall global heat transport problem:

- How do changes in the oceanic heat transport influence the atmosphere?
- What are the most influential features of the oceanic heat transport system affecting the atmospheric variability?

Sequences of increasingly specific questions follow from the above, and these are posed in the subsequent sections.

In order to predict climate change, we must deal with the complexity of the earth as a system, where significant changes may take place gradually over centuries or relatively dramatically over a time period encompassing the lives of a few human generations. We can not afford to wait while we accumulate adequate time series of basic geophysical variables, nor can we afford to undertake what inadvertently might become irreversible *in situ* "experiments" on the climate system itself.

Consequently, even more so than with the weather prediction problem, we must depend to a great extent on development of sophisticated computer models that can be used to perform various numerical experiments (hypothesis testing, sensitivity analysis, simulation, diagnosis and predictions). Data on the past behavior of the climate system will also be necessary. Back beyond about two centuries in time, these data must be derived from indirect sources of information, such as lake levels and ice cores. These reconstructed time series will serve to define the behavior that we seek to understand. The retrospective data will be used, along with current data from monitoring systems, in the model development (verification, calibration, and assimilation) and applications (simulations and predictions) portions of the NOAA program. Understanding gained from well-formulated research efforts into the fundamental oceanic processes and circulation patterns will serve to advance the development of the circulation models. Diagnostic efforts and simulations using the advanced models provide more sophisticated insights into the climate system, refine the research questions and so forth (Figure 2).

Calibrated and verified models that can explain the past behavior of the climate system, including "global climate changes" in prehistoric and even historic times (e.g., the Little Ice Age) will eventually provide the basis for reliable predictions and assessments of future changes in the world's climate system. An early step in the process will involve application of surface wind stress fields reconstructed from about a century of historic observations to simulate the global ocean circulation. The corresponding historic record of SST (Sea Surface Temperature) observations, including the position of oceanic fronts, will be used along with the sparser records of land-based observations to simulate the past circulation patterns of the atmosphere. Limited historical records of subsurface ocean observations are available for validation.

On climate time scales, most of the true external forcing functions are now variable: they must be explicitly dealt with in the prediction problem. Also, the land, ocean and cryosphere are fully coupled to the atmosphere in both a dynamic (mechanical energy) and thermodynamic (thermal energy) sense (Figure 1). If we look at the climate prediction problem from the side of the atmosphere, what had been essentially fixed ocean, land and cryosphere boundary conditions for the weather prediction problem become time-variable as we address the longer climate time scales. For example, the sea surface tem-

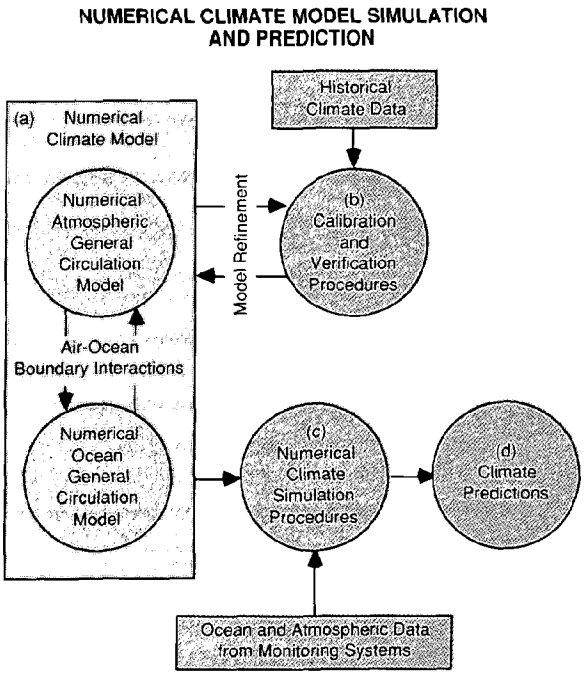


Figure 2: Application of Ocean Circulation Models and Ocean Data in Climate Simulation and Prediction. Ocean data (circulation, thermodynamic state, surface fluxes) provide (a) initial/boundary values for ocean circulation models coupled with atmosphere General Circulation Models (GCMs) and models for cryospheric and terrestrial interactions, (b) identification and removal of systematic errors in historical data for use in the climate model calibration and verification process, and as statistical constraints (in data assimilation mode) for (c) simulations and (d) predictions of climate changes.

peratures shift, significantly with the seasons, as does the land surface albedo and sea ice extent.

On time scales beyond the seasonal, the dissipative processes cause the atmosphere to "lose memory" of the initial conditions, so that the boundary conditions dominate the behavior of the atmosphere on long time-scales. However, the natural response times of the oceans, cryosphere and solid land are much longer than those of the atmosphere. Consequently, while the atmospheric side of the climate system is dominated by boundary conditions on climate time scales, the initial conditions for the oceans and cryosphere will still play a major role in the prediction problem for the total climate system. Hence, observations of the present state of the oceans are essential for model initialization.

Oceanic relationships to the boundary condition dominated features of the atmospheric system are certainly candidates for focused research. Experience with the GARP (Global Atmospheric Research Program) and GATE (GARP Atlantic Tropical Experiment) programs brought early recognition that a climate program would need to focus on numerical modeling as a basic means, and prediction of climate change on different time scales as a basic end. Furthermore, the understanding of the roles of the oceans' transport of momentum and heat (including interactions with the cryosphere) were seen as being decisive for the development and application of climate models. In the seminal GARP document (Döös, *et al.*, 1975), it was emphasized: "On seasonal, annual and decadal time scales, climate models must take into account an interactive upper ocean and sea ice... On long time scales (e.g., 100 to 1000 years), consideration must be given also to changes in the deep ocean and the variations of the continental ice sheets... The role of the oceans is believed to be a dominant one on climatic time scales."

1.2 How is Change Manifested in the Climate System?

Two decades ago, E. Lorenz (1968) speculated that the large scale behavior of the climate system may exhibit nonlinear instability under certain circumstances, particularly for its long term behavior. Evidence for this kind of behavior in the global climate system is the apparent abruptness of the onset of at least three major cooling episodes or glaciations over the last 150,000 years. The evidence suggests that a substantial portion of the cooling effect may have been experienced within the interval of about a century (Lamb, 1982). There also is evidence that less dramatic examples of sudden transitions in the climate system have taken place within the last 150 years. Fletcher *et al.* (1979 a,b) noticed sudden drops in the strength of the Southern hemisphere Westerlies in 1870, 1903 and 1917.

The conventional concept for climate change sees long-term change taking place continuously and gradually as a quasi-linear process. Many adherents of the greenhouse warming hypothesis accept this concept implicitly and expect change to take place as a gradual, more or less irreversible trend. The evidence for a gradual global warming since the beginning of the industrial revolution in the mid-eighteenth century is usually taken to support this gradualistic concept of climate change.

However, Broecker (1987 a, b) has presented a challenge to this conventional view of climate change. He points out the evidence for a number of very rapid transitions, mostly from and occasionally to, cold periods (including full blown Ice Ages) and

cites evidence that dramatic changes in atmospheric carbon dioxide content may have been involved in such climate changes. He also concludes that the evidence suggests a key role for some mechanism in the North Atlantic involving a shut-down of the Atlantic portion of the density/salinity-driven deep circulation (thermohaline circulation, Figure 3) transporting the excess cold waters of the Atlantic into the Pacific. Recently, Manabe and Stouffer (1988) have demonstrated numerically, using a coupled ocean-atmosphere simulation model, the existence of a bistable equilibrium condition for the climate system, at least within the approximations and limitations of the model.

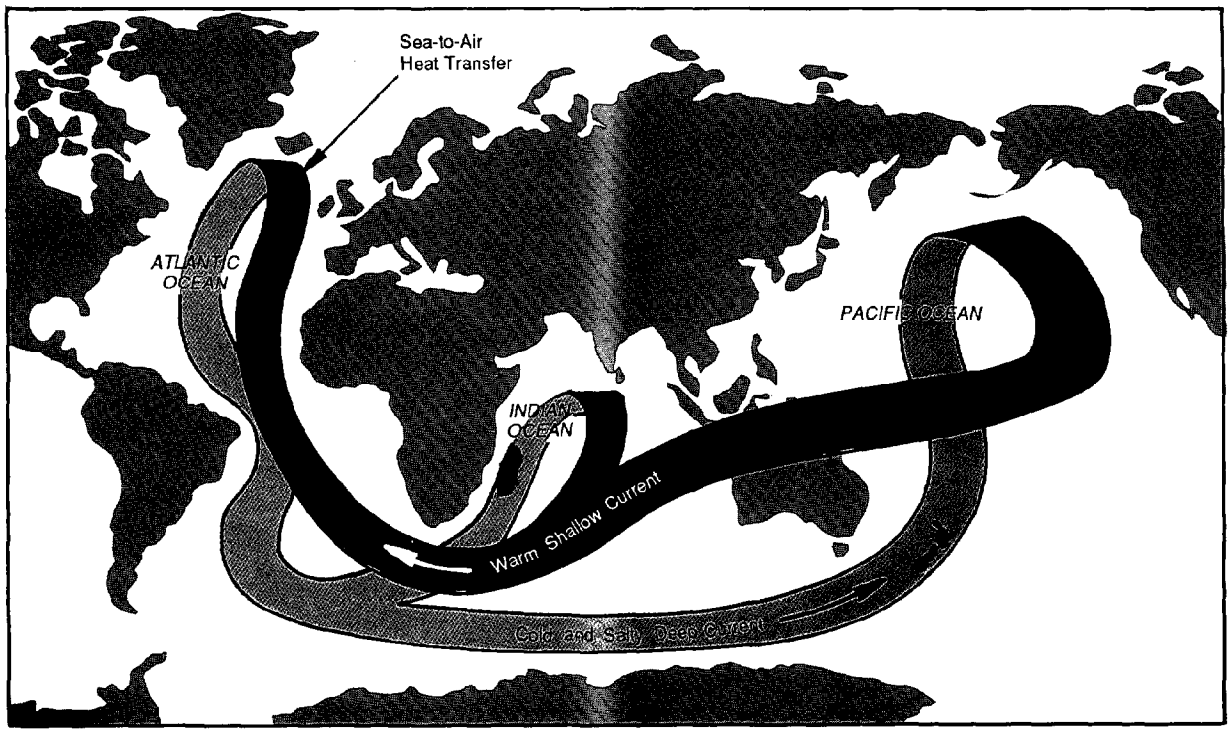
Such a bistable state involves two modes of the climate heat engine having markedly different statistical averages of the principal variables (i.e., climate). Each mode is stable for a wide range of boundary values and forcing conditions, but both states are simultaneously possible for a relatively narrow range of the boundary and forcing conditions. The climate system can make relatively rapid transitions between the two modes of the bistable state, under the conditions where both modes can exist. The climate system is actually unstable for that narrow range of conditions and markedly increased variability over a range of frequencies can be expected.

Basic observations concerning the role of the thermohaline circulation in long-term climate change suggest that high latitudes are regions of critical processes (including ice processes) and that salinity changes are critical, if not decisive, for the operation (or shut-down) of the thermohaline circulation system (Bryan *et al.*, 1988). Hence, changes in salinity (along with temperature) are the key observables that must be mapped and monitored. Other important observables are related to surface fluxes, interactions with major wind fields, and sea ice interactions.

2.0 Physical, Geographical and Programmatic Basis for the Ocean Climate Research Strategy

The field of global sea surface temperatures is generally recognized as a key climatological variable, as it is the major boundary condition related to the forcing of the atmospheric circulation that is also reflective of ocean processes. Analyses of the avail-

Figure 3: The Great Ocean Conveyor Belt (Broeker, 1987b). A simplified view of the thermohaline circulation system of the global oceans.



able SST records (see for example Folland *et al.*, 1986, and Parker, 1987) identify three prominent modes of temporal variability, other than the annual signal. These are: an interannual signal representative of the El Nino related phenomena and having a mainly tropical ocean focus, a signal reflecting interdecadal fluctuations, and a long term warming trend. It is tempting to identify the long term trend as being a secular change due to greenhouse warming, but given the limited duration of the available record it can only be characterized as representative of century scale or longer fluctuations.

2.1 Spatial Characteristics of the Major Climate Signals in the Ocean

The strongest, most coherent, interannual climate signals known are in the Equatorial Pacific and are categorized as ENSO (El-Nino-Southern Oscillation) phenomena. The ENSO manifestations include: the see-saw oscillation (Southern Oscillation) in atmospheric pressure as recorded in Darwin, Australia in the West, and Tahiti in the Eastern Equatorial Pacific; El Nino, the strong thermal anomaly in the Eastern Tropical Pacific, off the Peruvian and Ecuadorian Coasts; and the general pattern of tropical Pacific temperature and sea level anomalies and propagation of trans-Pacific Kelvin and Rossby waves. There seems to be some degree of correspondence in the Equatorial Atlantic, but whatever signal exists there does not seem to be as strong or coherent. An example of a relatively pronounced interannual signal in the Equatorial Atlantic is the upwelling in the Gulf of Guinea in the Eastern Tropical Atlantic.

The climates of the major land areas of the Pacific basin (Australia, New Zealand, Coastal China, Peru, and California) also tend to show a strong interannual signal as the dominant effect at climate frequencies lower than the seasonal/annual band. Generally, the interannual signal in the Pacific tends to become weaker and less coherent at higher latitudes, but remains pronounced nevertheless.

In the Atlantic, the signal strength and coherence of the interannual signal are also diminished as we move away from the Equator, and diminished overall compared to the Pacific manifestations. In the Northern Atlantic, the interannual oscillation frequently is not as pronounced as the decadal/interdecadal climate signals (Cayan, 1987).

The decadal/interdecadal signal shows almost an opposite character from the interannual signal with respect to its geographic distribution. Generally, the relative strength of the interdecadal signal is stronger in the Atlantic Ocean and Atlantic basin land areas than it is in the Pacific, at least outside of the Tropics (Cayan, 1987). The most prominent interdecadal climate signals relate to the Saharan/Sahel drought in North Africa, and the Mid-Western drought cycle of the United States, while the drought pattern in Northeastern Brazil near the equator does not exhibit a relative prominence of the interdecadal component of the signal over the interannual (Lamb *et al.*, 1986). The relative strength of the interdecadal climate signal compared to the interannual oscillations tends to increase as we move North and South away from the Equator in both oceans.

The relative strengths of the interannual and interdecadal climate signals over the globe can be described as a stronger interannual effect modulated by a weaker interdecadal signal for the Tropical Pacific basin as a whole. To some degree this holds true for the Equatorial Atlantic. A stronger interdecadal signal modulated by a weaker interannual effect tends to be more characteristic in the higher latitudes.

2.2 An Approach to Program Prioritization and Sequencing

A possible sequence of global ocean circulation programs, prioritized as to allocation of resources, and designed to make rapid progress in understanding of climate change on the interannual through interdecadal/century time scales, might start with the interannual signal. It mostly involves the ocean surface, atmosphere and some major surface current systems. Measurements in the lower atmosphere and within the ocean surface layers are the most cost effective. The Equatorial Pacific, with the best defined and localized effects of this kind, would appear to be the best place to start, subsequently moving outward to the Tropics, then the middle latitudes in the Pacific or the Equatorial Atlantic. The neighboring Indian Ocean, which behaves sympathetically with the Equatorial Pacific, would also receive early attention. The Atlantic equatorial and tropical zones could follow next if not given attention earlier, and higher latitude areas of the Pacific and Atlantic would probably be last.

At some point, the study of the interdecadal signal and the deeper ocean, with the greater associated costs and technical difficulties, would get underway. Again, the best place to start would also be where the interdecadal signal trends to be clearest and strongest and that would be in the North Atlantic, probably

following to the South Atlantic, the South and North Pacific.

This broad strategic approach to programmatic prioritization and sequencing is, in essence, what NOAA has been following since the inception of the OACIS (Ocean-Atmosphere Climate Interaction Study) program in 1984, and in certain respects for the last ten years since about 1979. OACIS, which was the predecessor of the TOGA (Tropical Ocean and Global Atmosphere) Program, and TOGA itself, set the strategy firmly in the mode described, for the interannual process by 1985 (Figure 4). The STACS (Subtropical Atlantic Climate Studies) Program set the pattern for the decadal problem with its Atlantic emphasis in 1982.

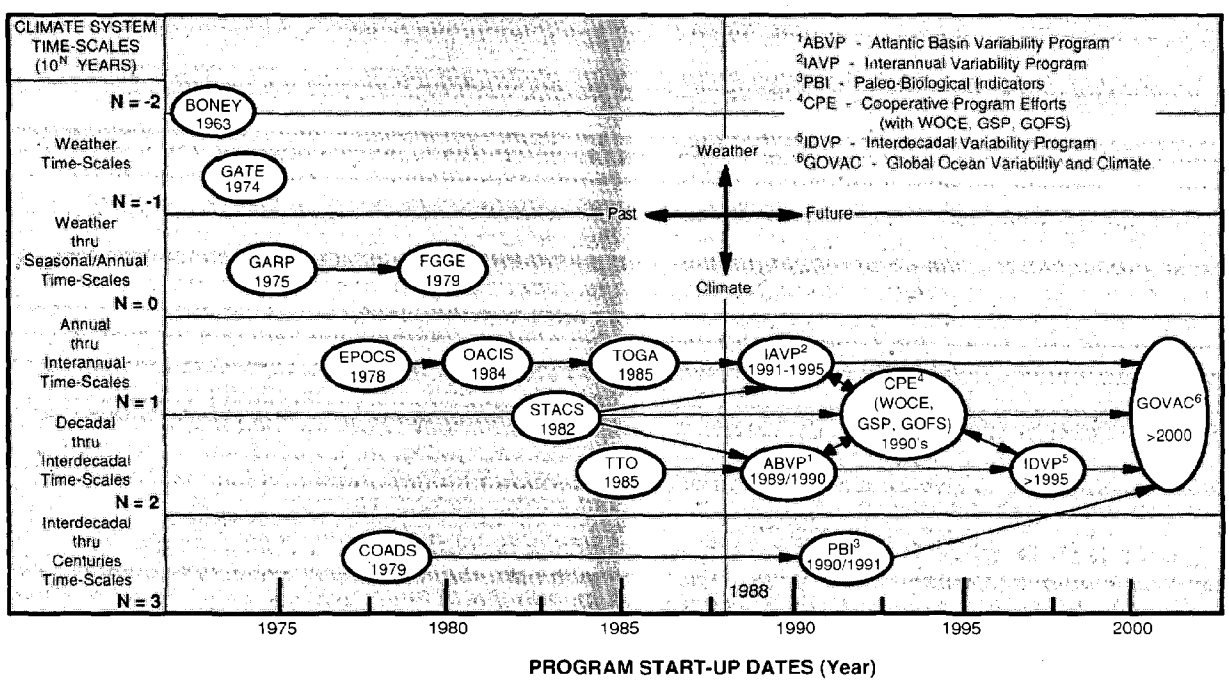
The prioritization described above would be flexible. Certain investigations might be conducted in geographical areas out of the suggested sequence. Any critical features of the ocean surface fields involved in the forcing of the global climate heat engine would be candidates for special priority. Examples include regions of high wind stress in the Southern Indian and South Atlantic Oceans, the Antarctic Convergence Zone and major oceanic fronts in the North Western Atlantic and North Western Pacific Oceans.

Figure 4 Evolution of NOAA Ocean Climate Programs. A summary view of NOAA/OAR ocean climate programs since 1975 with meteorological antecedents since 1963, and projected programmatic strategy through the first decade after the year 2000.

2.3 The Programmatic Foundations of the Research Strategy

The programmatic basis of the NOAA research strategy in ocean-climate, as articulated in the 1979 plan (Fletcher, *et al.*, 1979), led to a series of budgetary initiatives for specific program elements over the next few years. Out of this planning and budgetary process, emerged four new core programs (see Figure 4) which were to form the foundation of the NOAA programmatic strategy in ocean-climate research for the next decade.

All four core programs have supported the development of basic means (technology and techniques) required to conduct subsequent programs. All except the Comprehensive Ocean-Atmosphere Data Set (COADS) effort, have focused upon specific regional problems and basic processes that are representative of important aspects of the general ocean-climate system critical to the development of understanding of climate change. COADS is fundamentally global in concept and approach, but with regional resolution. Together, the four programs cover the entire frequency band in the climate system identified as the concern of NOAA's long-term effort (seasons through centuries) and represent the essential first steps toward realizing the overall predictive goals.



2.3.1 The EPOCS and STACS Programs

Two of the core programs, Equatorial Pacific Ocean-Climate Studies (EPOCS) and STACS, are the earliest and are officially funded as ongoing base programs to this day. In 1978/79, NOAA initiated the EPOCS program to study the causes of the large scale sea surface anomalies in the equatorial Pacific and their effects on the atmosphere. The Equatorial and Tropical SST distribution is believed to be a major factor in the forcing of the atmospheric component of the global climate heat engine. Because of the large interannual signal in sea surface temperature in the eastern equatorial Pacific, initial studies were directed at this region.

Oceanic heat flux is generally believed to be an important process involved in interdecadal climate variability. However, long-term monitoring of the sub-surface ocean processes on interdecadal time scales presents a formidable challenge. In 1982, NOAA began the STACS program for studying the transport of equatorial heat to higher latitudes in the Atlantic and related processes. The initial emphasis of STACS was directed at the western boundary currents of the North Atlantic Subtropical Gyre, in particular, the Florida Current and Gulf Stream, which have been shown to be a major component in the wind-driven modes of Atlantic heat flux and the subtropical gyre. Given the interdecadal and interannual implications of the program, it is shown in Figure 4 as based upon both of these frequency bands.

2.3.2 The TTO Efforts

A third effort, Transient Tracers in the Oceans (TTO), has been intermittently funded as an internal effort supporting other programs, and has been directed at a sequence of regional problems having much broader implications for climate. The 1979 NOAA strategy document noted that plans were underway for one study, "Transient Tracers in the Ocean," using "radio-carbon and tritium tracers," to study "residence times, transport mechanics and vertical mixing." However, under the subsequent budgetary constraints, the tritium work was judged to be too expensive for NOAA's limited resources, so that chloroflourocarbons (freons) became the focus of NOAA's chemical tracer work in the mid- 1980's. The chloroflourocarbon tracer studies had the additional advantage of being complementary with other global chemistry and carbon dioxide flux work supporting NOAA's ocean climatic mission, i.e., the ocean's role in the greenhouse problem. The work has progressed at a low funding level, but has proceeded more or less continuously, supporting other NOAA climate research programs.

2.3.3 The COADS Effort

The fourth effort, the Comprehensive Ocean-Atmosphere Data Set (COADS), is also internally funded and has continued at a steady low level of effort for nearly a decade, but unlike the other three, does not involve an actual field measurement program. COADS represents a systematic attempt to use past data sets relevant to ocean climate on time scales beyond a decade or two. Since 1854, ships of many countries have been taking regular observations of local weather, sea surface temperature, and many other characteristics near the boundary between the ocean and the atmosphere. In later years, fixed research vessels, buoys and other devices have contributed similar marine reports. The collection of surface data spanning the global oceans, from the mid-nineteenth century to date, is the historical ocean-atmosphere record utilized in the COADS effort. Together, these four programs form the four legs upon which the NOAA ocean-climate strategy stands.

2.3.4 Ocean and Climate Dynamics Modeling Efforts

A fifth set of programmatic efforts not identified in Figure 4 started earlier than the others, and will assume growing importance in the future. This is the ocean circulation/climate dynamics modeling developments that have been ongoing as base efforts in the Geophysical Fluid Dynamics Laboratory (GFDL) since the mid 1960's. These model developments and numerical experiments also cover the entire climate frequency band of concern. Like COADS, they do not involve field work, but are involved in development of essential techniques needed to achieve the ultimate predictive goals of the program.

3.0 The Programmatic Research Strategy for Interannual Variability of the Oceans

Since the inception of EPOCS in 1978, NOAA's ocean-climate research strategy for interannual time scales has been executed through a sequence of specific programs: EPOCS, OACIS, and TOGA (see Figure 4). EPOCS concentrated on the equatorial ocean between about 20 degrees N and 10 degrees S latitude, with the major initial emphasis on the dominant equatorial Pacific Ocean phenomena. In 1983, starting with the EPOCS scientific plan, the National Academy of Sciences (NAS) produced a national plan for a program called OACIS that was directed toward the problem of interannual climate variability. NOAA initiated its part of OACIS in 1984, building around the continuing EPOCS effort. When the World Climate Research Program (WCRP) adopted the strategy of OACIS, it was developed as a full international program called TOGA. In 1985, NOAA subsumed the EPOCS and OACIS efforts under the international program plan (see Figure 4).

3.1 The TOGA Program

The program title, TOGA, defines the essence of the main concern: the role of the dominant interannual processes of the tropical ocean and its interactions with the global atmosphere producing interannual climate variability.

After extensive review and debate, the TOGA Program proceeded with the broad strategic concept outlined in Section 2.0, continuing to concentrate resources allocated to investigations in the interannual climate research area, first for investigations of low latitude Pacific Ocean processes, then moving outward to higher latitudes (Tropics and Subtropics) in the Pacific, the Indian Ocean, then the tropical Atlantic, etc.

During the initial implementation stage of TOGA, the major concern was the strong equatorial Pacific warmings which occur at irregular intervals of about 2-7 years. However, now both diagnostic studies and theoretical work have more clearly delineated the global tropical linkages associated with ENSO variability. Recent work also indicates an important role of the large-amplitude, coherent atmospheric fluctuations on the intraseasonal timescale (30-60 day waves). As a result, the current description and understanding of tropical ocean-atmosphere variability involves a broadened focus for TOGA to include the, as yet poorly understood, "global teleconnections," relating global interannual oceanic and atmospheric phenomena. The full ENSO cycle, rather than just the warm episodes, and the intraseasonal mode of variability also are included in the new focus.

The limits of the tropics, by usual definition, are confined by the ± 30 degrees latitude band, which accounts for about one half of the Earth's surface. However, as a practical matter the ocean concerns of TOGA are approximately bounded by the ± 40 degrees latitude band, providing a beginning to extension of the monitoring system into the mid-latitudes. The extension of the monitoring system is essential for understanding the nature of the teleconnections.

The massive Pacific warm episode of 1982-83 was associated with a clearly defined pattern of interocean teleconnections around the equatorial belt. These evolved over a period of about three years to include a strong and well defined global signal in rainfall, atmospheric circulation and SST. New analyses of the historical data have shown this to be a recurrent mode of interannual global variability in the tropical ocean and atmosphere.

The tropical Atlantic also has a mode of interannual variability that has many similarities with the Pacific Ocean manifestation of ENSO. The tropical Atlantic measurement program under TOGA during the next several years aims at providing data to check the hypothesis that changes in the position of the Intertropical Convergence Zone (ITCZ) relate to changes in the heat content of the equatorial zone. These efforts, which will probably extend beyond the TOGA time-line, are also candidates for TOGA interactions with the World Ocean Circulation Experiment (WOCE) Core 3 Project that is concerned with ocean gyre dynamics.

3.2 Interannual Ocean Variability Research in the Decade of the 1990's

The 1990's will be a period of intense interagency and international research in the oceans, involving at least two major NSF-led programs: WOCE, concerned with basin scale ocean circulation, and the Global Ocean Flux Study (GOFS), concerned with surface fluxes in the global ocean. These programs offer important opportunities for cooperative efforts with NOAA programs. With leveraged interagency efforts, achievement of the predictive goals of the NOAA program becomes feasible. Therefore, it is important that NOAA have its main programmatic

thrusts on both interannual and interdecadal ocean-climate variability in place by the early 1990's. Figure 4 shows the existence of these Cooperative Program Efforts (CPE) for the decade of the 1990's.

STACS, concerned with deriving climate indices for western boundary current phenomena, is shown in Figure 4 as, more or less, operating off-line by itself before interacting with the interannual and interdecadal ocean-climate program elements in the early 1990's. By that time, STACS will have accumulated about a decade of time series needed to address the cross-effects between the interdecadal and interannual time scales, particularly in the sub-tropics, in time to interact with the new elements designed to address these questions in the early 1990's.

TOGA probably can not answer all of the important research questions concerning the ocean's role in interannual climate variability within existing levels of resources and within a single decade. A follow-on program will need to continue investigations into the more complex issues of higher latitude responses and the global ocean that may have been started under TOGA.

The follow-on program is tentatively named Interannual Variability Program (IAVP) (Figure 4). In actuality, it may be an expansion and extension of TOGA. The broader based program must build upon both EPOCS and STACS, rather than mainly EPOCS as has been the initial situation with TOGA. Also, this program will need to interact with a NOAA interdecadal ocean variability program element having an Atlantic Ocean focus (see Figure 4). Activities discussed below could be initiated, either as part of a new interannual variability program, or under the later stages of the present TOGA effort.

The EPOCS, TOGA and the STACS programs need to be enhanced by observations in new areas, while continuing observations in selected areas already explored on an operational monitoring basis. The area of EPOCS and TOGA (or post-TOGA) research should be expanded poleward to include interactions of the equatorial/tropical circulation systems and subtropical gyre circulation in both the Atlantic and Pacific, and the area of STACS concern should be increased equatorward for the same reason. The same observational framework applied in the earlier stages of STACS and TOGA should be used in the enhancement: two to three years of intensive observing periods should be directed at identifying important indices and the methodology to monitor the indices.

Priority also must be given to full expansion of monitoring and research effort into the Atlantic and Indian Ocean basins, in order to examine the possible role of ocean processes in these areas in African and Brazilian drought, and the effect on ENSO of water mass exchange between the Indian and Pacific Oceans. The problem of ocean-atmosphere "teleconnections", particularly involving mid-and-high latitudes will probably remain a conundrum, so long as the observational framework remains confined to the traditional TOGA ± 40 degrees latitude band, and mainly in the Pacific/Indian Ocean Basins. In addition to expansion of observational networks, cooperation between program elements focusing on both interannual and interdecadal variability (Figure 4) will be essential for progress in understanding the true causal mechanisms for the teleconnections.

3.3 The Meridional Heat Transport System in the Oceans

Meridional circulation involves the overturning of the ocean. It brings into play both the surface and intermediate layers of the ocean and the deep and bottom layers. Hence, the aspects of the ocean circulation that relate to interannual and interdecadal phenomena must be connected through the meridional circulation. Recent model and observational results suggest that we need to have a better understanding of the meridional heat transport from the tropics and its variability. For instance, some model simulations of the ocean indicate that the time scale of El Nino events is determined by, the heat loss from the tropics during a warm episode and, the time required to replenish the western Pacific warm pool.

Meridional heat transport is crucial in both the cooling and warming processes of the global climate heat engine. In the Atlantic, unlike the Pacific, there is considerable northward heat flux across the equator, related to the thermohaline circulation in that basin. Variability in this cross-equatorial flux will have important implications to heat flux further north. In both basins, processes on the western boundary apparently have a large influence on meridional heat flux. A better understanding of the interaction between the equatorial circulation and the subtropical gyres, with particular emphasis on the western boundaries, is required.

The meridional heat flux away from the equator in the tropics and the cross equatorial heat/chemical tracer fluxes are key components of the global description of ocean circulation required by global change studies. Measurement of these transports near the equator requires that special consideration be given to the likely importance of boundary condi-

tions (particularly in the Atlantic), abyssal circulation, and the failure of the geostrophic approximation at the equator. However, coupling a deep circulation study to the upper ocean TOGA (or post-TOGA) program, as indicated by the various interannual and interdecadal program interactions in Figure 4, and utilizing the satellite altimeter and wind fields available during WOCE will permit a coordinated attack on this problem.

The meridional velocities generally are small compared to the prominent zonal currents. A combination of direct and indirect techniques are going to be required to estimate these flows. The program will require:

- Zonal transects at tropical latitudes (±10°) to measure density and chemical tracer distributions. These sections should be repeated after about five years, with modifications based upon what has been learned in the intervening period of time.
- Meridional cross equatorial transects (10°N to 10°S) of tracers in the western, central and eastern regions. Enhancement of the TOGA/Post-TOGA upper ocean thermal field measurement program by including salinity measurements. Determination of surface currents with surface drifters and satellite altimetry; constant level drifters may also be needed in very high latitudes.
- Determination of surface wind fields and wind stress using satellite based scatterometer instruments and island meteorological stations in those broad areas of the oceans where the thermohaline circulation is believed to be at the surface or within the mixed layer.
- Integration of the above measurements with the GFDL high resolution model in order to estimate meridional transports and refine the overall picture.
- Exploration of eddy variability in tropical regions and assessment of the importance of eddy heat flux.

Long-term monitoring would then follow the exploratory studies. Other aspects of the research effort directed toward questions related to the meridional circulation and its relationship to interdecadal and interannual research elements are discussed in Section 4.2.

Following the over-all programmatic strategy outlined in Section 2.0, the next emphasis should be on the decadal, interdecadal and longer time scale ocean processes including possible mechanisms of potentially rapid climate change. The important role that the Atlantic Ocean Basin appears to play in and the thermohaline circulation and the importance of the interdecadal signal in the climate of neighboring land areas of the North Atlantic make it high priority as an early focus of research into the interdecadal ocean variability problem. However, when we look at the implied scope of the program, involving both the Southern and Northern Atlantic Oceans, including polar and near-polar regions, as well as the equatorial ocean area (with emphasis now including deep water processes), the task remains great. Furthermore, NOAA lacks experience in some of these areas, such as the Antarctic/Southern Ocean.

One practical solution is to create a highly leveraged NOAA program, strongly cooperative with other (mostly non-NOAA) programs scheduled to get underway in the early 1990's. Since the NOAA objectives are, for the most part, not the same as those of the other programs, the NOAA effort can not simply depend passively upon the non-NOAA efforts. The other non-NOAA programs are more of a pure research nature, in which understanding of processes and overall dynamics is the main goal, although guided by climate concerns to some degree. However, NOAA's efforts must be directed at development of predictive capability for the climate system on longer time-scales, and establishing the essential base-line observational networks needed for the diagnostic and predictive applications. To do this, the NOAA program must also be long-term.

In many ways, the Atlantic Basin Variability (ABVP) effort identified in Figure 4 is an analogy of TOGA, but there are essential differences. TOGA is an intense ten-year effort, built upon a strong ongoing base funded NOAA effort in the Pacific

(EPOCS) which is directed to core questions. The ABVP effort will build upon STACS to some degree, but must provide continuing funding for the other core effort (TTO), that has never been formally funded. The ocean tracer work must now also be applied on a long-term basis in the Atlantic (it has been ongoing in the Pacific), specifically for the interdecadal problem.

The ABVP must form a permanent core program continuing through to an expanded global ocean interdecadal variability focused research effort sometime later in the 1990's. Tentatively, this expanded focus is shown as a new program element, the Interdecadal Variability Program (IDVP), in Figure 4.

In the context of understanding the mean circulation, interdecadal changes, and the meridional transports of heat and gases, it is clear that studies related to global climate change must include the intermediate and deep circulations and their interactions. Modeling has been very successful in simulating the upper equatorial ocean in the TOGA Program, but the deep water circulation has received less attention. It is known, however, that the meridional overturning and deep flows across the equator play a very important role in the global heat balance. In the Atlantic, the mean annual heat flux is northward across the equator, a dramatic contrast to the symmetrical poleward pattern in the Pacific. Decadal changes in this flux have been suggested as a mechanism for forcing atmospheric circulation changes. Major regional climate questions such as the source of rainfall variability in the Sahel, northeast Brazil and the U.S. Great Plains may be intimately tied to ocean variability in the Atlantic basin.

More specifically, recent paleoclimatic studies have substantiated the variability of North Atlantic thermohaline circulation as a major factor in the initiation of warming and cooling events observed in the climate record. This is supported by coupled ocean-atmosphere model results that suggest that the global climate system may be characterized by two stable states that differ primarily by the presence or absence of the global circulation cell associated with North Atlantic deep water formation. The geographic constraint of the areas of deep water formation being in the Atlantic suggest this region as an area of early emphasis.

In the Atlantic, the considerable northward heat flux across the equator may be related to the thermohaline circulation in that basin. Therefore, variability in this cross-equatorial flux will have important implications to heat flux further north.

In both the Atlantic and Pacific basins, processes on the western boundaries apparently have a large influence on meridional heat flux. A better understanding of the interaction between the equatorial circulation and the subtropical gyres, with particular emphasis on the western boundaries, is clearly required.

The vertical pathways between the surface and deeper layers of the ocean must be modelled correctly in order to simulate the effects of atmospheric carbon dioxide on climate and natural climate variability on longer time scales. The most valuable data sets for verifying that the vertical pathways have been included in ocean circulation models correctly are measurements of transient tracers, such as the freons, tritium and bomb-produced carbon-14. For this reason the transient tracer program in WOCE is of particular importance for the continued development of NOAA models.

The freon measurements taken by NOAA in its own TTO program in the North Pacific are a unique resource in this respect, and this program should serve as the basis for similar observations in the Atlantic and in particular, those high latitude areas (North and South in the Atlantic Basin) where deep water renewal occurs. Activities in the Antarctic and high latitudes of the North Atlantic, associated with deep water formations and the thermohaline circulation, will involve extensive NOAA participation in other programs on an international basis.

Another component of the early Atlantic variability activities will be initiation of an Atlantic Volunteer Observing Ship (VOS) program, similar in system design to the VOS program which has been invaluable in the support of TOGA Pacific activities. The proposed Atlantic VOS will provide improved upper ocean thermal fields for atmosphere-ocean interaction studies.

It should be noted that deep XBT units are now available, but are considerably more costly than the standard ones now widely used. Hence, the deep application units will probably need to be concentrated in the very high latitude and equatorial areas emphasized here, and if applied elsewhere, will probably need to be "coarsely" interspersed with standard XBT units. Observations and monitoring strategies are made cost-effective by applying results of modeling diagnostic studies of the systems being analyzed.

[illegible] of NOAA Interdecadal [illegible] NOAA [illegible] Programs

Separation of the interannual and interdecadal variability effects is only a convenient artifact of the programmatic strategy constrained by limited resources. Clean separation of physical processes and circulation based on characteristic frequency is only approximate. Consequently, a later research focus, perhaps an independent program element, ultimately may be needed to address the full range of questions concerning the combined interannual through interdecadal climate variabilities on a true "global ocean-global atmosphere" basis. This is tentatively designated in Figure 4 as Global Ocean Variability and Climate (GOVAC) for startup in the 1995-2000 time frame. However, certain critical questions will require coordination of interannual and interdecadal research efforts prior to that time.

The internal NOAA ocean-circulation related programs that will support the ABVP effort are STACS, which already has been dealing with long-term measurements of gyre variability in the Sub-tropical Atlantic, EPOCS and TOGA/Post-TOGA (Section 3.0), which must deal with the equatorial Atlantic and the mid- latitude connections on interannual time scales that are strongly coupled with the interdecadal effects of gyre dynamics and interactions in the Atlantic tropical areas. Any TOGA/Post-TOGA Atlantic variability work will need to be well coordinated with the ABVP effort. A possible example of such a coordinated TOGA-ABVP project might concern the branching of the Atlantic Equatorial Current at the geographical "nose" area of Brazil, between 5 degrees and 8 degrees S latitude. North or South shifts in the axis of the branching current system will affect the transport of warm South Atlantic water into the Caribbean and the Gulf Stream (Lamb, 1972) and consequently is related to both interannual and interdecadal climate variability in the Atlantic basin. There also remains a possibility of an international program effort of some kind in this area, that would allow broader based cooperative efforts. Again the NOAA concerns would be directed toward the long-term and development of predictive capabilities.

4.2.1 Research Related to the Meridional Heat Flux

First, in the Atlantic, the objective is to derive indices for such cross-equatorial, western boundary features as the Deep Western Boundary Current (a major component of the thermohaline circulation of the North Atlantic) and surface currents. Modeling and observational studies suggest that both of these features play an important role in meridional heat flux. During the intensive observing period, direct current, water mass and water mass age observations need to be taken. To trace water masses, an indication of cross-equatorial flow, nutrients (e.g., silicate and phosphate) coupled with oxygen need to be used. To study water mass ages, helium/tritium ratios for short time scales (months to years) and halocarbons for longer time scales (decades) need to be applied. The latter approach has recently been utilized to trace Deep Western Boundary Current waters across the equator.

Later on in the Pacific, the strategic emphasis should include intermediate water mass formation. In contrast to the Atlantic, there is apparently no deep water formation in the North Pacific. Thus, by process of elimination, meridional heat flux is probably strongly related to circulation of intermediate waters. Process studies in the critical formation regions of these waters, and large-scale mapping of their distribution using tracers, are required. In the approach described here, the heat flux away from the equator and the cross equatorial heat/chemical tracer fluxes are key components of the global description of ocean circulation required by global climate change studies. Aspects of research concerned with the meridional circulation have been discussed in Section 3.3.

4.2.2 Regional Climate Variability: Relationship to Ocean Processes

A major part of the problem confronting human institutions in making use of climate forecasts is that global average conditions have little meaning locally. Generally, a local or regional manifestation of a global change is significantly more extreme than the global average. Our insights into the regional implications of global change are not well developed. The impetus for this line of research is the long-term (ten years or longer) ecological consequences and the near-term human impacts (less than ten years) resulting from

large and long-lived climate fluctuations. The complexity of the climate system, and the volume and variety of data that are needed, require a strategy directed initially at a selected subset of these critical regional problems.

Present research reveals regional problems that might yield to concerted study, based in part on observational evidence linking ocean surface parameters to regional variations, and in part on evidence from experimentation with atmospheric General Circulation Models (GCM's). Sea surface temperature (SST) anomaly patterns have been correlated with U.S. weather patterns on interseasonal to interannual time scales. For instance, El Nino SST anomaly patterns have been used with some success to predict atmospheric conditions over portions of the U.S. Mid-latitude SST anomaly distributions in the Pacific have been used in a similar mode. In the Atlantic, tropical SST distributions have been used to predict Brazilian and African rainfall patterns. At higher latitudes, SST distributions have been correlated with European rainfall. Much of the atmospheric variability occurs in the form of the teleconnection patterns observed in pressure fields at various heights.

Although the evidence is weaker, other studies indicate changes in the atmospheric circulation patterns and corresponding changes in regional weather patterns on decadal time scales. These changes are known to be related to changes in the strength of the global atmospheric circulation, which in turn is probably related to variability in oceanic thermal forcing of the atmosphere. For instance, winter season air temperature, precipitation and synoptic weather system frequency over the contiguous U.S., and drought in the Great Plains have been shown to vary on decadal and longer time scales in phase with large scale atmospheric circulation patterns over the U.S. These patterns, in turn, depend on Pacific SST patterns.

The number, severity and genesis of extratropical storms along the Atlantic coast of the U.S. has increased from the 1920's to the 1960's, with post-1960's distributions similar to pre-1920's distributions. Similar long-term variability has also been observed in other regional climate features such as the Sahel drought. A concentrated effort is now warranted to increase our understanding of the role of large scale atmosphere-ocean interactions in regional climate variability, in order to develop regional prediction capability.

As already noted, the issue of interdecadal variability cannot be completely disassociated from the interannual oscillations, particularly in the mid-latitudes and higher zones in the Atlantic Basin, or even the Pacific Basin outside of the Tropics. Observational and modeling studies of mechanisms affecting large-scale, ocean-atmosphere variability (focusing on the Atlantic Basin, North and South America, Europe, and Africa) at time scales on the order of decades, but including the interannual modulation, need to be undertaken as soon as possible. This includes critical questions such as the wider role of ENSO events.

4.3 Coordination of NOAA Interdecadal Research with Other National and International Programs

A variety of national and international programs having common interests, or complimentary concerns, with the NOAA research objectives on interdecadal time scales are in various stages of planning and development. Most are scheduled to get underway during the decade of the 1990's, offering important opportunities for cooperative efforts.

4.3.1 The World Ocean Circulation Experiment

The international WOCE program under the World Climate Program (WCP), with the national WOCE program led by the NSF, will be the main external programs of concern to the ABVP. The national program is mainly concerned with the description of the global ocean circulation and processes on the decadal/interdecadal scale, which are designated as part of the Core 1 Project under the international scientific plan for WOCE. The Core 1 large scale observational network and hydrographic program will involve the Atlantic (as well as other oceans) and should provide opportunities for cooperative efforts with NOAA. However, more important opportunities for the ABVP effort may be with the Core 2 Project (The Southern Ocean Project) and with Core 3 (The Gyre Dynamics Experiment).

The international WOCE Core 2 Project concerns correspond very closely with the ABVP concerns. The Core 2 Project (Gordon *et al.*, 1987) has designated a "spoked wheel" plan composed of nineteen deep vertical sections between Antarctica and the 30 degree S latitude zonal line. Three of these lines are designated by the Core 2 Project as "choke points" with lines for repeated monitoring and deployment of bottom pressure sensors and long-term coherent current meter arrays. The Drake Passage, alone, would have a permanent monitoring system consisting of

bottom pressure gauges, closely spaced moored arrays (intensive transport array) of current meters, temperature and conductivity sensors. Ship based CTD profiles to the bottom and XBT casts would be taken on all lines. Oceanic tracer samples are also proposed in these areas.

The three "choke point" lines are clear candidates for a possible cooperative effort by NOAA, as is the ocean tracer work.

An E-M cable system is not mentioned as part of the long-term Drake Passage monitoring system, so that STACS and the ABVP may be able to contribute such a system in a joint effort. It should also be noted that W. Emery ran hydrographic surveys essentially along some of the same lines about a decade ago as part of the FGGE Program, so that a baseline, in part, already exists. NOAA could support repeats of these lines on a regular, long-term basis as part of the ABVP Program and contribution to WOCE.

The Gyre Dynamics Experiment part of the international WOCE (WOCE Core 3, 1987) appears to be focusing on the North Atlantic, perhaps with some South Atlantic work and a possible deep circulation experiment in the Brazil Basin. The concerns appear to be highly compatible with the ABVP strategy. There will be a component of the Core 3 effort concerned with meridional circulation and deep convection driven by diabatic processes as involved in both deep water formation in the sub-polar areas and warm 18 degree water formation in the sub-tropics.

Another Core 3 concern involves the sub-polar frontal exchanges (at the boundary of the sub-tropical and sub-polar gyres). Tracer work is also proposed along with hydrographic surveys, velocity floats and moored systems. The NOAA concerns in ABVP would seem to stress gyre interactions in both the equatorial/tropical area and high latitudes in both southern and northern hemispheres. The surface fronts at the boundaries of the subpolar gyres and subtropical gyres in both the Northern and Southern hemisphere are singled out for special attention. These interactions are associated in the South Atlantic with the important convergence zone near the Antarctic Circumpolar Current. Hence, cooperative opportunities with Core 3 efforts appear promising. Also, STACS-type cable systems are not explicitly listed for Core 3, so that this could provide a unique NOAA contribution to any cooperative effort. Also, the area of WOCE concerns cuts off at the 60 degree N latitude line, whereas NOAA interests will go to still higher latitudes. NOAA's contribution to a cooperative effort could involve determination of the Northern boundary conditions for the WOCE efforts.

4.3.2 The Greenland Sea Project

The Arctic Ocean Sciences Board (NAS, 1977) has proposed a Greenland Sea Project (GSP) which has a number of international participants, including certain science funding or policy levels of governments, other than the United States. Given the similar interests between the proposed GSP and the Atlantic variability strategy outlined here, NOAA would be a logical candidate to undertake the U.S. agency role. The project's region of study is consistent with the identified area for NOAA's North Atlantic climate concerns.

The project is concerned with water mass production, sea ice variability and its relationship to climate, and atmospheric exchanges driving the system. Geochemical tracer work, modeling, deployment of moored arrays of current meters, tracked surface drifters, pressure gauges are all proposed. However, E-M cable efforts are not explicitly proposed. The passages between Iceland and Greenland and between Spitsbergen and Greenland offer potential locations for such deployments, although the other sides of Greenland and Spitzbergen facing Northern Europe pose more design questions and implementation problems. Again, STACS technology, or advanced developments of that technology (see Section 5.0), may be applicable here, as would NOAA transient tracer work and related carbon dioxide flux and ocean process research.

4.3.3 The Global Ocean Flux Study

The NSF-led Global Ocean Flux Study (GOFS) project (Brewer, 1986) is concerned with a variety of surface processes and fluxes, including those involving carbon dioxide. The NOAA program must be concerned with surface fluxes of fresh water, latent and sensible heat, and carbon dioxide, so that mutually advantageous inter-relations between the Atlantic component of GOFS and the NOAA program seem both feasible and desirable. In this respect, the NOAA effort may be able to complement GOFS by concentrating on the ocean margins and the shoreward edges of the ocean boundary currents (both western and eastern).

4.4 Addressing the Role of the Oceans in Climate Variability

There is evidence of a long-term trend in the time series of some climatic variables over the past century or so. However, the earliest studies by Fletcher, Radok and Slutz (1979) indicated that climate variability on the decadal to centuries time scale is dominated by only a few abrupt adjustments of the circulation regime, rather than by gradual change. The evidence of the greatly expanded COADS data set now reinforces that conclusion. However, questions have lingered about possible systematic errors due to changes in measurement technology and practices, and the transition from sailing vessels to steam powered ships. Every effort has been made over the years to identify and remove sources of systematic error, but it is difficult to prove that no systematic error sources remain when one cannot repeat the observations under controlled conditions.

Consequently, efforts are continuing to compare the COADS data with indirect historical and paleoclimatic evidence. These are mostly from land areas, and range from the historical record of Nile River flood levels at Cairo, lake sediments in Africa, and ice core data. The records generally show changes of an abrupt nature correlated with the transitions indicated in the COADS series. One implication of the observed sudden transitions is that we need much longer retrospective time-series for numerical model development and verification purposes. Longer oceanic retrospective time-series are preferred over land series, as being more directly indicative of past ocean circulation patterns.

Since we have mostly reached the historical limits of scientific observations with COADS, indirect sources will be required. Since these indirect sources are inherently very "noisy" data that are difficult to interpret, redundancy of many data types will be needed to produce statistically based reliability in their interpretation. Ship logs may be one source, but there is another. Man has been fishing on the ocean surface for as long as he has been sailing upon it, and fish catch and whaling records indicating changes in species populations and their patterns of behavior exist going back centuries. These records overlap with the COADS data in some of the same areas since the nineteenth century. These can also be correlated with studies of mud layers (varves) in areas where sedimentation rates are laid down ten or more times as rapidly as the world average ocean sedimentation rate. It may be possible to calibrate fish scales and other paleo-biological evidence in the varves by comparison with written historical fish population records and the whole sequence of overlapping direct and indirect ocean records, beginning with COADS (Sharp and De Vries, 1988). In principal at least, these can be extended back for several millennia. Such a paleo-biological component of a comprehensive NOAA Climate and Global Change Program needs to be developed (Figure 4).

The strategic approach involves the application of these long time series with computer simulation models. If sudden changes are indeed characteristic of climate change on interdecadal and longer time scales, there will be a particular problem in simulating the actual transition processes. Typically, a nonlinear system undergoing such a transition, reorganizes itself so that boundary layer processes and other sub-grid effects become critical, at least during the transition. Unfortunately, lack of resolution of the models leads to parameterizations that are usually based upon assumptions dependent upon the existing state of the system, which may be incompatible with transitional conditions and the future state.

An atmospheric GCM, or ocean circulation model, is simply a discretization of the known equations of motion of the atmosphere (or ocean), with physical processes treated explicitly when possible (radiation, orography, large scale precipitation, etc.), and parameterized when necessary (cumulus convection, small scale mixing, etc.). The mix between explicitly computed and parameterized processes changes as the resolution increases. For example, if the resolution could be refined to one kilometer, it would no longer be necessary to parameterize cumulus clouds because they would be explicitly resolved. Since model resolution is purely a function of the capability of computer technology, we can expect models to improve as advances in computer technology allow higher resolution. This progress will be slow, since every doubling of resolution involves 16 times more computation. Doubling of the resolution in each of the two horizontal spatial dimensions, multiplied by the mandatory reduction in the temporal step size, and assuming that the number of vertical layers in the model is also doubled, accounts for the factor of 16.

A national effort is being made to develop supercomputers, and climate modeling is considered to be the prime nondefense application of these machines. NOAA will need to update its computing facilities as these new generation machines become available. This will require a more frequent updating of GFDL

computers from the present ten-year cycle to an accelerated five- year cycle or less as dictated by the actual advances in computer systems, if we are to achieve important modeling capabilities, such as simulation of transition regimes between climate states.

5.0 Technology Development Requirements

It is imperative that NOAA continue to develop, on a more systematic basis, technology for monitoring climatically important oceanographic processes. Both shipboard and *in situ* instrumentation are required. In particular, an acoustic Doppler velocity profiler which can be deployed on ships of opportunity is needed to provide global distributions of surface velocities, an important variable for climate model validation. Similarly, accurate meteorological packages, including sensors to determine surface energy fluxes, are required for installation on ships-of-opportunity.

A "scientific cable" is necessary for use in locations other than straits and passages where land-to-land connections are possible. The cable should be designed to provide data on the internal structure of the ocean, rather than merely total transport, as does the present cable system. A possible array would consist of suites of instruments connected by cable and having remotely programmable sensor packages located at selected positions on the seafloor.

Other electromagnetic methods for measuring large-scale variations in ocean transport are promising. The electromagnetic methods that are ideal candidates for measurements of ocean transport variations are: (1) voltage measurements using passive or active telephone submarine cables that span ocean currents, (2) bottom horizontal electric field measurements, (3) surface and bottom vertical electric field measurements, (4) bottom horizontal magnetic field measurements, and (5) accurately towed electric field measurements.

Cross stream cable voltage measurements yield accurate and continuous real time measurements of the transport variations in the Florida Current. The development of inexpensive cable laying techniques therefore should be started for continuously monitoring the transport variations of other important ocean currents. The use of existing submarine telephone cables should also continue to be explored as these measurements will be the least expensive of any of the electromagnetic methods. Trans-oceanic telephone cables might yield direct evidence of heat flux variations if long period temperature and other possible noise of the power stations can be accurately monitored.

The point electromagnetic measurements, developed and successfully used in deep ocean magnetotelluric studies, may also prove to be valuable because of the inherent spatial smoothing (vertically and horizontally) of the electromagnetic signals and the lower costs of deployment compared to installing cables. An array of bottom magnetic and electric measurements should be tested as an alternative to cross stream cable voltages. Such arrays will be useful in regions such as the Arctic where it is not feasible to install long cables.

The vertical electric field is useful as a measure of the magnetic east-west transport, but will not provide any horizontal spatial averaging since the vertical electric currents are small due to the effects of the insulating atmosphere. Such measurements would be particularly useful in the equatorial regions where the flow is predominantly east-west.

Finally, accurately towed electric field measurements will provide the important regional survey of the ocean currents; namely, its extent and spatial variations. This information will be needed to design the minimum cable length and the maximum spacing allowed between the sea floor point electromagnetic recorders.

6.0 Summary

With the development of a predictive capability for climate changes taking place over a range of time scales as a goal, the concept of the climate system as a "heat engine" with two working fluids (the atmosphere and the oceans) provides an effective metaphor for formulating the critical questions that must be answered. The questions can be structured into a hierarchy going from the most general to the very specific. At the top of the hierarchy, the most general question concerns the temporal and spatial variability of both the effective forcing fields and the variability of the response of the two working fluids on different characteristic time scales.

The research strategy is designed to answer the important questions. At the most general level of approach, the strategy seeks to recover retrospective information on the past behavior of the climate system and to use this information, along with data from present monitoring systems, for calibration, initial conditions and boundary conditions for com-

puter simulation models of the climate system. The computer simulation models involve the coupling of the atmospheric and oceanic general circulations and the interactions with the land areas of the earth and cryosphere. The simulation models must be sequentially refined in an iterative process from the information gained through focused process research, diagnostic studies and vigorous comparisons of simulation results with known past climatic variability patterns and current data from monitoring systems. Predictions emerge from this process by numerically carrying forward in time the projections of the calibrated and validated models.

Knowledge of the characteristics of the climate signal on different time scales and in the difficult regions of the world oceans allow ordering of the research priorities and structuring of the research into programmatic components. A plan involving the development of a sequence of programmatic steps is summarized in Figure 4.0. While the program units shown are not intended to be definitive at this time, the questions that they are designed to answer are critical and the programmatic structure supporting the research strategy that is formally adopted will need to provide those answers.

A specific research issue of importance that concerns the role of the oceans in interannual climate variability is the effect on ENSO of water mass exchanges between the Indian and Pacific Oceans. On interdecadal and longer time scales, important research concerns include: (1) the role of North Atlantic deep water formation, and exchanges with the northern branches of the subtropical gyre, in regulating the thermohaline circulation, and (2) the identification of feedback control mechanisms in the Atlantic thermohaline circulation and their role in possible major, and relatively sudden, climate changes taking place on the century time scale. On both interannual and interdecadal time scales, some of the important research questions relate to: (1) understanding the dynamics of the ocean/atmosphere fluxes of heat, moisture and momentum, particularly with respect to areas controlling the time- variability of water mass formation, (2) the relationship of changes of heat content of the equatorial zones and changes in the position of the ITCZ and their relationship to climate variability in higher latitudes, particularly in the Atlantic basin.

Other questions, some more specific and some more general, have also been posed. Still, other questions will emerge from the learning process of the research itself.

References

Brewer,P. G., *et al.*, 1986, "The Global Ocean Flux Study (GOFS): Status of the U.S. GOFS Program," *EOS*, 67, 827-837.

Broecker, W.S., 1987 a, "Unpleasant Surprises In The Greenhouse," *Nature*, 328, pp. 123-126.

Broecker, W. S., 1987 b, "The Biggest Chill," *Natural History*, 96 pp. 74-83.

Bryan, K., Manabe, S., and Spelman, M. J., 1988, Interhemispheric Asymmetry in the Transient Response of A Coupled Ocean-Atmosphere Model to A Carbon Dioxide Forcing, NOAA/GFDL, Princeton University, Princeton, New Jersey, in press.

Cayan, D. R., 1987, "Low Frequency Variability of SST and Its Relationship to Atmospheric Forcing," Proceedings of the Twelfth Annual Climate Diagnostics Workshop, U. S. Department of Commerce, NOAA, NWS, pp 167-178.

Döös, B. R., *et al.*, 1975, "The Physical Basis of Climate and Climate Modeling," GARP Publication Series No. 16, ICSU/WMO.

EPOCS, 1982, EPOC's: Equatorial Pacific Ocean Climate Studies, U.S. Department of Commerce, NOAA, ERL, Boulder, Colorado.

Fletcher, J. O., *et al.*, 1979, An Ocean Research Plan, U.S. Department of Commerce, NOAA, ERL, Boulder, Colorado.

Fletcher, J. O., Radok, U., and Slutz, R., 1979, "Climate Signals of the Antarctic Ocean," presented to: Symposium on Progress in Antarctic Meteorology, XXIIth General Assembly of IUGG, Canberra, Australia.

Folland, C. K., Parker, D. E., Ward, M. N., and A. W. Colman, 1986, "Sahel Rainfall, Northern Hemisphere Circulation Anomalies and Worldwide Sea Temperature Changes,"Proceedings of the Pontifical Academy of Sciences Study Week, Vatican, 23-27, September 1986, also U. K. Meteorological Office Long-Range Forecasting and Climate Research Series, Report No. LRFC 7A, Sept. 1986, Amended July 1987.

Gordon, A. L., *et al.*, 1987, The Southern Ocean, WOCE Core Project 2 Planning Meeting, Bremerhaven 20-23, May 1986, WCP/ICSU/SCOR.

GSP, 1987, Greenland Sea Project: An International Plan of the Arctic Ocean Sciences Board, National Academy Press, Washington, D.C.

Lamb, H. H., 1982, *Climate History and the Modern World*, Methuen, London and New York 387 pp.

Lamb, H. H., 1972, *Climate: Present, Past and Future–Volume 1 Fundamentals and Climate Now*, Methuen, London, 1972, 613 pp.

Lamb, P.J., Peppler, R.A., and S. Hastenrath, 1986, "Interannual Variability in the Tropical Atlantic," *Nature*. 322, pp. 238-240.

Lorenz, E. N., 1968, "Climatic Determinism," *Meteorological Monographs*, vol. 8, No. 30, pp 1-3.

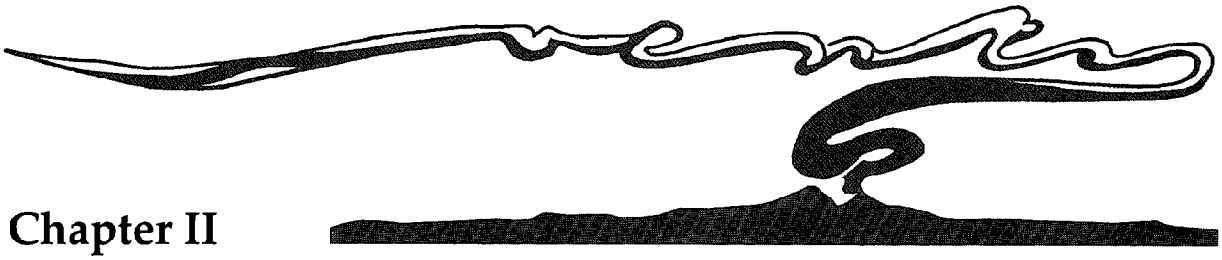
Manabe, S. and Stouffer, R. J., 1988, Two Stable Equilibria Of A Coupled Ocean-Atmosphere Model, NOAA/GFDL, Princeton University, Princeton, New Jersey, in press.

Parker, D. E., 1987, "The Sensitivity of Estimates of Global and Hemispheric Marine Temperatures to Limitations in Geographical Coverage," U. K. Meteorological Office Long-Range Forecasting and Climate Research Series, Report No. LRFC 12, April 1987.

Sharp, G. and T. J. DeVries, 1988, Paleocology Workshop, NOAA, NSF and U. of S. Carolina, S. Carolina.

STACS, 1982, STACS, Subtropical Atlantic Climate Studies, Program Development Plan, U. S. Department of Commerce, NOAA, ERL, Boulder, Colorado.

WCP-WOCE, 1987, "The Gyre Dynamics Experiment, WOCE Core Project 3 Planning Meeting, London, 2-5 September 1986, WCP/ICSU/SCOR.



Chapter II

RIDGEFLUX
Hydrothermal Venting on a Global Scale

Executive Summary

Problem and Opportunity

Ocean basins can no longer be considered to be merely passive sinks for materials transported to them by subaerial erosional processes. Indeed, ocean basins, by virtue of their containing the worldwide seafloor spreading center system, are now known to host active processes which are having significant effects on the chemical, heat and mass budgets of sea water. Just as plate tectonics revolutionized earth sciences in the '60s, dynamic processes now known to occur worldwide at seafloor spreading centers, in particular hydrothermal venting processes, are becoming an analogous focus for marine science for the '90s.

Hydrothermal venting affects the global chemical compositions of the ocean and underlying sediments through long-term input of numerous chemical elements and dissolved gasses including silica, iron, phosphorous and CO_2. The global oceanic budgets of silica and phosphorous, for example, are especially important because they are micronutrients which play major roles in the biogeochemical cycles of the sea. Hydrothermal venting is also directly responsible for the evolution of a globally distributed major and heretofore totally unknown vent fauna ecosystem.

Research Strategy

An unequivocal demonstration of hydrothermal influence on the regional chemistry of major portions of ocean basins would allow NOAA to take a major step forward in quantifying the global significance of submarine hydrothermal venting.

The central operating hypothesis that OAR can test is the following:

- *Hydrothermal venting plays a major role in controlling chemical budgets of the world ocean.*

Testing this hypothesis requires work in four principal areas. These research efforts will help determine, in order to predict, the effects of hydrothermal venting on the chemistry of the ocean environment.

- *Source strength of hydrothermal emissions integrated over ridge segments and their relationship to underlying geologic structure and processes,*
- *Regional transport of conservative and nonconservative hydrothermal emissions, including*
- *Hydrothermal emission loss rates from the water column, and,*
- *Temporal variability of hydrothermal emissions at time scales of 10^{-4} to $>10^5$ years.*

These processes will be studied at distances ranging from meters to several hundred kilometers from active hydrothermal sources. Far-field (>100km) studies will focus on the regional extent, age and evolution of chemical anomalies. Mid-field (1 km to 100 km) scale investigations will focus on the axis of seafloor spreading centers and their segmentation. Near field (< 1 m to 1 km) investigations will concentrate on detailed geologic analysis and mapping of targeted vent fluids, and temporal and chemical studies of vent emissions.

Why Now?

Seafloor hydrothermal venting, which was discovered in the late '70's, is now known to be a global phenomenon. The full range of seafloor spreading center processes and the magnitude of their effects throughout the world ocean are, however, still in a stage of discovery. Growing numbers of investigations are clearly showing that these processes are not isolated but are distributed throughout the world ocean and it is also clear that these processes have persisted as fundamental contributions to ocean chemical budgets for hundreds of millions of years. Recent results suggest positive correlations between major plate motion changes, increases in seafloor hydrothermal activity (with accompanying changes in chemical flux rates to the ocean), and long-term climate change. NOAA, in collaboration with other government and academic investigators, is studying regional chemical oceanographic effects in the North Pacific which may be the result of hydrothermal activity taking place along the seafloor spreading center systems off the West coast of the U.S. Most recently, NOAA has discovered an entirely new type of hydrothermal activity. In 1986 and again in 1987, NOAA researchers detected and studied large episodic bursts of hydrothermal activity occurring over the Northern Pacific seafloor spreading center, which, in a single event, contained quantities of heat and mass equivalent to year-long continuous hydrothermal output of entire ridge segments. These and other discoveries compel NOAA to continue, and expand, its unique national role for quantitatively understanding and predicting effects of hydrothermal processes.

Why NOAA?

NOAA's research mandate includes the responsibility to understand and assess global chemical processes that continually alter the composition of the oceans, their sediments, and their life. The remoteness of the deep ocean seafloor spreading centers requires extensive and very sophisticated research platforms and instrumentation. NOAA has, in addition to its research responsibilities, unique capabilities for undertaking the necessary field work to understand ridgecrest processes including highly specialized research vessels, manned and remote submergence vehicles, high-resolution bathymetric and photographic systems, and prototype vent chemical monitoring and vent fluid sampling systems.

Benefits

Among the benefits of NOAA hydrothermal research are, (1) new numerical models for chemical fluxes in the oceans, (2) acquisition of critical data for establishing models for circulation of heat and chemicals in the ocean, and (3) development of deepsea technology which will make it feasible to address the global scope of the hydrothermal impact.

1.0 Background

1.1 Discovery, Seafloor Tectonic Regimes

The discovery of warm and hot springs at the Galapagos (Corliss *et al.*,1979) and East Pacific Rise (Rise Project Group, 1980) spreading centers confirmed the existence of mineral rich hydrothermal fluids emanating from seafloor vents. Associated with the vents were massive polymetallic sulfides and a diverse and unique animal community with an ecology completely dependent upon chemoautotrophic bacteria. In succeeding years, a growing number of investigations at other spreading centers in the Pacific and, most recently, the Atlantic Ocean, have documented the existence of many other venting systems. It now appears that hot springs may be found, more on less commonly, along the entire 65,000 km length of the worldwide seafloor spreading center system.

Subducting margins may also play an important role in affecting the regional, if not global, oceanographic budgets of dissolved elemental species and gasses, notably methane. Recently Kulm *et al.*, (1986) have discovered extensive areas where sedimentary prisms along the subducting margin of the U.S. west coast are being compressed and faulted with an accompanying release of large quantities of methane, iron, manganese, ammonia, barium, and other nutrients. In comparison with hydrothermal vents, these "cold" vents, too, are replete with abundant, but biologically distinct, exotic fauna. Subduction zones are nearly equivalent in length to spreading centers. In terms of the global extent of such environments,

the mass flux from these regions may be shown to rival the seafloor spreading centers and other volcanic regions within the ocean basins.

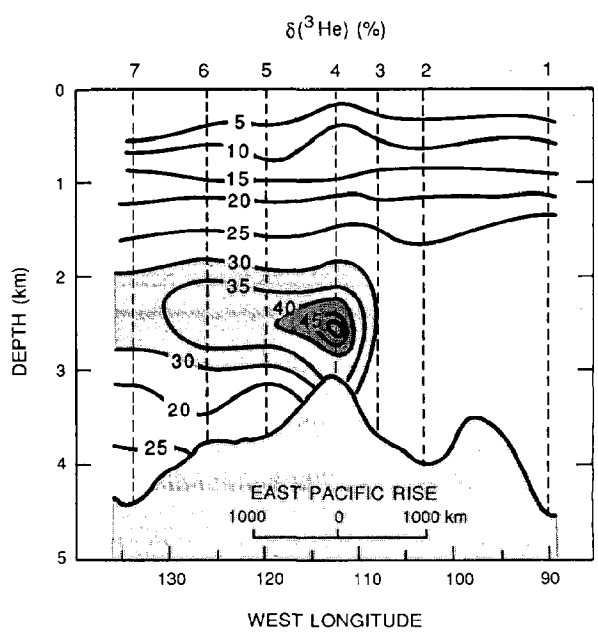
1.2 Relationships: Chemistry, Heat, and Circulation

Prior to the discovery of seafloor springs, the ocean basins were considered passive sinks for materials weathered from continents and transported into the oceans by rivers and wind. Discovery of the mid-depth $\delta(^3He)$ anomaly in the Pacific (Clarke *et al.*, 1969) was an early indication that the ocean basins themselves were, at least for some conservative elemental species, active sources of a magnitude that significantly affected the global ocean environment. Subsequent sampling of vent fluids (Edmond *et al.*, 1979 a,b; Edmond, 1981) and observations of basin scale plumes of ^3He originating on the East Pacific Rise (Lupton and Craig,1981; Riser, 1985) have confirmed the global impact of hydrothermal emissions (Figure 1). [Note: The $^3He/^4He$ isotope anomalies in natural waters are defined as the percentage "delta" values relative to the atmospheric $^3He/^4He$ ratio, $\delta(^3He) = (R/R_{atm}^{-1})*100$, where $R=^3He/^4He$. A $\delta(^3He)$ value of approximately 70 indicates an essentially pure source of ^3He from the earth's mantle.]

Most hydrothermal constituents, however, are not conservative in seawater. Their contributions to the oceans are determined by a process of normalization with the assumed conservative hydrothermal supplies of ^3He and heat. For example, Edmond *et al.* (1979a,b) and Edmond (1981) used hot spring data from the Galapagos spreading center and 21°N on the East Pacific Rise to estimate global fluxes of both major and minor elements from submarine hot springs. By assuming that the majority of chemical fluxes were from 350°C hot springs and that the $\delta(^3He)$ versus heat and other elemental heat ratios were uniform between vent systems, they estimated that Li, Rb, Ca, Si, and Ba are released in amounts comparable to or greater than the terrestrial input to the oceans. In addition, the Mn input from hydrothermal sources is sufficient to account for its entire authigenic inventory in deep sea sediments. On the other hand, Mg and SO_4 are removed as percolating seawater interacts with basalt, so spreading centers are the major sinks for these species. The more sophisticated approach of Thompson (1983), which considers low temperature as well as high temperature venting, has refined but not substantially altered the original flux estimates of Edmond *et al.* (1979a,b). Both estimates indicate that hydrothermal circulation plays a major role in the distribution and concentration of many elements within the global ocean. Since these estimates were made, active venting has been observed and some measurements made in the Atlantic Ocean along the mid-Atlantic Ridge (Rona, *et al.*,1986; Nelsen *et al.*, 1986/87). As a consequence, those earlier calculations, which were only able to assume other sources of venting, now have added credence. The recent discovery of episodic releases of massive amounts of heat and mass at the seafloor of the Juan de Fuca Ridge (Baker and Massoth, 1986a) suggests that short duration episodic events may be at least as important to the oceanic heat and mass budgets as the steady state inputs from the hot springs.

Hydrothermal circulation also has a global effect on the heat budget of the deep ocean. It is now estimated that hot springs and warm water vents account for 30 percent of the cooling of newly formed oceanic crust and 20 percent of the earth's total heat loss (Sclater *et al.*, 1980). The local and regional effects of the input of volcanic heat will vary according to the rates at which this heat is supplied to the oceans. Stommel (1982) has proposed that the heat flux over

Figure 1 Contours of $\delta(^3He)$ in section view over the East Pacific Rise at 15°S (after Lupton and Craig, 1981). [Note: The $^3He/^4He$ isotope anomalies in natural waters are defined as the percentage "delta" values relative to the atmospheric $^3He/^4He$ ratio, $\delta(^3He) = (R/R_{atm}-1)*100$, where $R = ^3He/^4He$. A $\delta(^3He)$ value of approximately 70 or higher indicates an essentially pure source of ^3He from the earth's mantle.]



a basin long active ridge is sufficient to alter mid-water circulation patterns. Joyce *et al.* (1986) have described a regional heat anomaly in the bottom water of the northeast Pacific Ocean that can be used as a unique tracer of the relative age of the bottom water.

1.3 Relationships: Geology, Space, and Time

Several geological factors appear to play a major role in determining the location and vigor of along-axis hydrothermal venting. These include the volcano-tectonic stage of evolution of the rift axis, the rate (continuous or episodic) at which volcanism and/or rifting occurs at the spreading axis, the proximity to subcrustal melting anomalies, the extent and depth of faulting, and the thickness of sediment cover. On a local scale, fracture pattern, bathymetric relief, and surface lava type may also influence the location and extent of venting. The relative importance of low-temperature or diffuse venting, either within or outside the rift axis, is presently unknown although the heat and mass flux from such sources may be large (Morton and Sleep,1985).

Continued observations along spreading centers, however, have demonstrated that venting has a different spatial and temporal variability than originally anticipated. While the association of major vent fields and long wavelength along-axis bathymetric highs remains valid, detailed surveying of individual ridge segments (Baker and Massoth, 1986a; Macdonald *et al.*, 1986) has revealed more extensive along-axis hydrothermal activity, implying that some ridges or ridge segments may be considered line sources of hydrothermal emissions to the surrounding ocean.

For chemical constituents of hydrothermal fluids that behave nonconservatively and rapidly precipitate in seawater, such as Mn and Fe, the impacts are more localized and are preserved as concentration anomalies in the sediments (Lyle, 1976; Lyle *et al.*, 1986; Metz and Trefrey, 1985). In such cases, the sedimentary record can provide a temporal history of hydrothermal venting. Recent studies of Deep Sea Drilling Project cores indicate that substantial increases in the flux of hydrothermal materials to the oceans occurred during the Cenozoic (Lyle *et al.*, 1986; Rea and Leinen, 1986). Some of these changes in the rate of hydrothermal input may have resulted insignificant changes in the earth's carbon budget and climate (Owen and Rea, 1985; Kasting and Richardson, 1985). The probable causes for these changes are that, as a result of tectonic rearrangements of seafloor spreading centers during the Eocene (and other periods) the input of hydrothermal CO_2 and other constituents increased to a level where oceanic concentrations were several times higher than the present. The concomitant release of CO_2 to the atmosphere was of sufficient magnitude to effect some of the global warming trends that were known to have occurred during those periods. The implication for the present day oceans and atmosphere is that hydrothermal effluents contribute to the overall balance of the carbon cycle in the oceans which, in turn, ultimately controls natural variations of CO_2 in the atmosphere.

The association of spatial and temporal hydrothermal variability is apparent at several scales. Long cores from the DSDP Program have been used to quantify low-frequency (>10^6 years) changes in hydro thermal activity caused by large-scale tectonic reorganizations in ridge structure (Owen and Rea,1985). Standard sediment cores have the unique potential for resolving hydrothermal flux variability on the order of 10^3 years within the last one million years. Leinen (1984), for example, has found factor of three changes in the accumulation rate of hydrothermal emissions from the Juan de Fuca Ridge in sediments of Brunhes age (<750,000 years). Detailed studies of hydrothermal emissions in sediments cored from the ridge systems may thus allow the determination of the history of hydrothermal processes on regional scales and their impact on paleo-environments within their respective ocean basins. On an even finer scale, the recent observation of an apparently brief but intense release of a large quantity of hydrothermal effluent from the southern Juan de Fuca Ridge–equal to about four years' production of a large vent field on the same ridge segment–indicates that high-frequency episodic processes may contribute substantially to the hydrothermal flux of material into the water column (Baker and Massoth, 1986a,b). These observations demonstrate that determination of the ridge integrated hydrothermal source strength will ultimately require determination of the spatial and temporal variability of venting over a broad range of scales.

Some data sets suggest an intriguing connection among basin wide anomalies in the distribution of heat, mass, and hydrothermal activity along a ridge

system. Reid (1982) attributes the tongue of relatively warm water extending 6000 km westward from the East Pacific Rise between 5°S and 20°S (Fig. 2) to hydrothermally emitted heat. Riser (1985) noted that this plume also shows elevated $\delta(^3He)$ concentrations and determined that the plume resulted from advection by large-scale abyssal flow and eddy diffusion processes. In the North Pacific, a basin-wide transect at 47°N reveals aubiquitous silicate maximum centered at 2000 m, the depth of the Juan de Fuca Ridge crest (L. Talley, pers. comm., Fig. 3). The 100-fold elevation of silicate in hydrothermal fluids from the Juan de Fuca Ridge (Von Damm and Bishoff, in press) suggests that this maximum may at least represent a residue of long-term hydrothermal venting into the mid-depth waters of the northeast Pacific. [Note: The global mass balance of Si in the oceans is particularly important because it is a micronutrient and, therefore, plays a major role inthe biogeochemical cycles of the sea.] Unequivocal establishment of a hydrothermal origin of the silicate maximum will require corroborating evidence from other conservative and nonconservative hydrothermal tracers. NOAA has already directed preliminary efforts at mapping large-scale features of hydrothermal emissions. Baker *et al.* (1985) identified a concentration maximum in particulate hydrothermal Fe extending westward from the southern Juan de Fuca Ridge for at least 100 km at ridge crest depths. Chemical and heat anomalies in the water column are extremely important because they can be used to determine the integrated effects of hydrothermal venting on time scales of decades to hundreds of years.

To deepen our understanding of the chemical composition and evolution of a regional hydrothermal plume requires a determination of the plume's

Figure 2 Potential temperature (°C) along the σ_3 = 41.50 isopycnal in the depth range between 2500-3500 meters (after Reid, 1982).

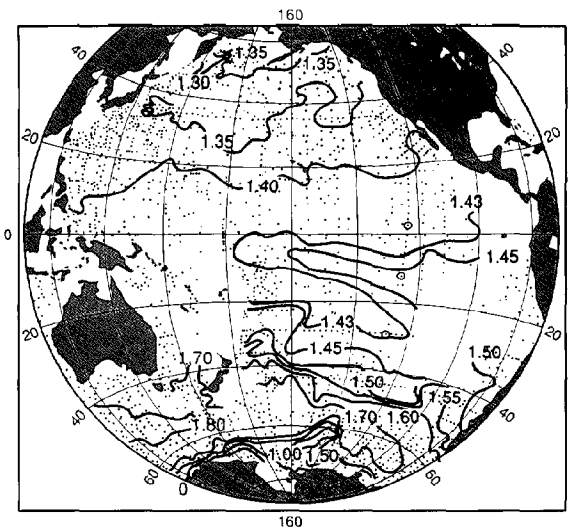
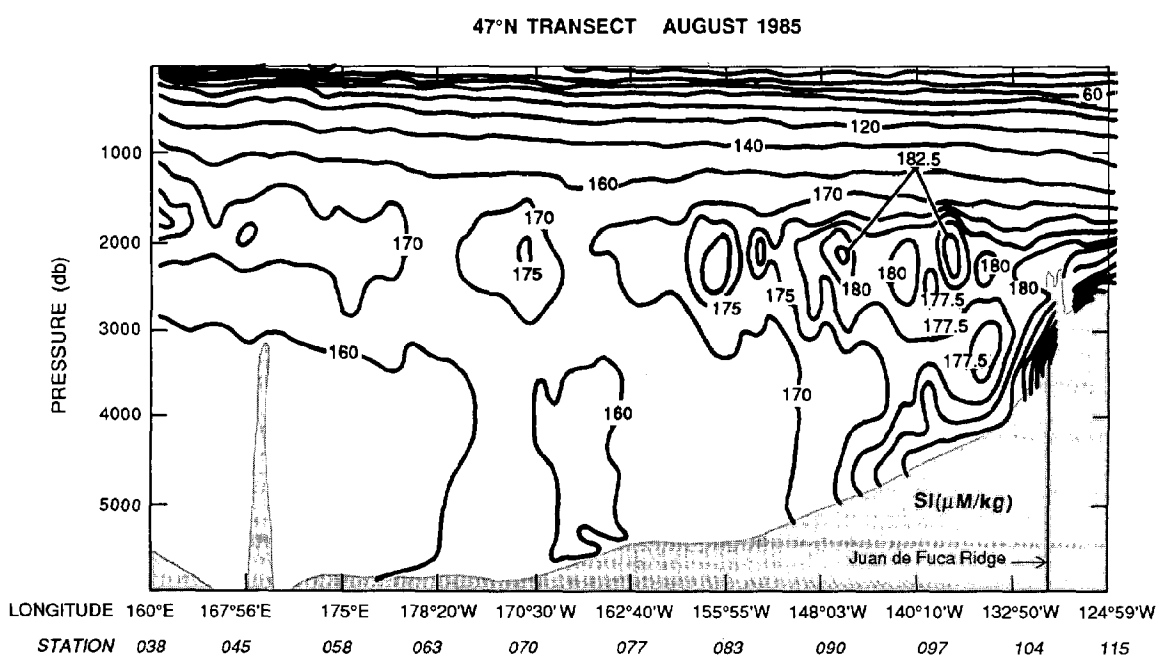


Figure 3 Distribution of dissolved silicate (SiO_3 µmol/ℓ) from an August, 1985, cruise along 47°N latitude. Station density shown by tick marks along the top (after Talley, Joyce, and Swift, in prep.).



origin at individual vent fields on various segments of the ridge crest. Sampling the integrated plume above each of three vent fields on different segments of the Juan de Fuca Ridge has shown each to be chemically distinct (Massoth *et al.*, 1985). Chemical diversity of lavas within a segment, interpreted as an indication of small-scale mantle heterogeneity, has been revealed by detailed dredging of the East Pacific Rise (Langmuir *et al.*, 1986). Intra-segment chemical diversity of plumes, arising from two distinct venting processes, i.e., "normal" chimneys in vent fields with a life span of tens or hundreds of years, and episodic venting with a life span of days or weeks, has been recently observed on the Juan de Fuca Ridge (Baker and Massoth, 1986a).

Changes of similar magnitude may also occur over shorter time periods, and the techniques to quantify higher frequency hydrothermal changes are in preliminary stages of development. *In situ* vent monitors will provide information on the temporal stability of the concentration of key chemical species in the undiluted fluid of individual vents. These sensors will also replace anecdotal information on the birth and death of individual vents with continuous and quantitative measurements. Even more challenging is the detection and study of brief and episodic, but potentially very large, events of volcanic and associated hydrothermal activity.

2.0 NOAA's Role in Marine Hydrothermal Research

Despite the growing awareness and measurements of hydrothermal activity, its quantitative influence on the character and composition of the global ocean and atmosphere is not yet known. With what is presently known, however, it is reasonable to hypothesize that seafloor venting does have a significant effect upon the chemical composition of the global oceans, and perhaps even the atmosphere.

Among NOAA's research missions is the responsibility to continually assess the state of the ocean from several perspectives. In addition to research focusing on physical and biological processes, NOAA's mission also mandates an evaluation of global chemical processes that continually alter the composition of the oceans, their sediments, and their life.

NOAA's base hydrothermal research program VENTS has been since 1984 principally directed toward achieving a quantitative and predictive assessment of hydrothermal venting occurring along the Juan de Fuca seafloor spreading system and it effects on the chemistry of the Northeast Pacific Ocean. The VENTS Program involves the collaborative efforts of other governmental agencies and universities bordering the northeast Pacific and has discovered numerous active vent sites along major segments of the Juan de Fuca Ridge as well as the first major site of venting in the Atlantic.

In order to better understand the linked processes of hydrothermal venting, chemical composition of oceans and atmosphere, and climate change, NOAA proposes an expanded program of observations and measurements along several ridge crests. *The RIDGEFLUX Program will emphasie the quantitative determination of global oceanic chemical effects of venting occurring over time scales extending from nearly instantaneous to geological.* Over short time intervals, processes will be monitored to discern the high-frequency content of the hydrothermal variation signal in order to be able to effectively design a long-term sampling and measuring strategy. Over longer time scales, the basin-wide dispersal of hydrothermal emissions from major portions of the global ridge crest will be quantified. Over the longest timescales, research will determine the historical causes and effects of venting preserved in the stratigraphic record. Integrating results at those time scales (and the corresponding space scales) should provide a basis for predicting the effects of venting on global changes to the oceans and atmosphere.

An initial step in quantifying the global impact of hydrothermal venting on ocean chemistry will be to examine carefully select active venting locations within the global ocean basin (Fig. 4). Building on the present NOAA/PMEL VENTS Program which is seeking to undertake such a mission in the northeast Pacific on the Gorda/Juan de Fuca/Explorer ridge system, RIDGEFLUX investigations will expand this quantitative approach to include other major venting regimes such as those recently found along the Mid-Atlantic ridge (Rona *et al.*, 1986). The Indian Ocean venting system is under investigation by French and English scientists. An unequivocal demonstration of hydrothermal influence on the regional chemistry of major portions of ocean basins would allow NOAA to make a major step forward in quantifying the global significance of submarine hydrothermal venting.

The central operating hypothesis of the RIDGEFLUX Program is thus:

- Hydrothermal venting plays a major role in controlling the chemical budgets of the world ocean.

Testing this hypothesis requires work in four principal areas:

- Ridge-integrated source strength of hydrothermal emissions and its relation to underlying geologic structure and processes,
- Regional transport of conservative and nonconservative hydrothermal emissions,
- Hydrothermal emission loss rates from the water column, and,
- Temporal variability of venting at scales of 10^{-4} to 10^{5} years.

The goal of the NOAA RIDGEFLUX Program is to determine, in order to predict, the effects of hydrothermal venting on the chemistry of the ocean environment. Research will emphasize measuring, or otherwise determining, the magnitude and composition of the present and historical vent flux integrated over major ridge systems. Such a task requires a large-scale observational measurement and modeling program, supported by specific process studies, to quantify the rates of input and loss of hydrothermal constituents such as heat, trace metals, SiO_2, He, and CO_2 at specific ridge segments.

2.1 Facilities and Instrumentation Requirements

Much of the needed equipment for the field work required for RIDGEFLUX are available from NOAA facilities. These are, for example, Class I research vessels, deep submergence vehicles (manned and unmanned), swath mapping systems (Sea Beam), water sampling systems (SLEUTH), corers, grab samplers, deep-tow camera systems. Many other systems are available for lease.

Systems for making long-term *in situ* observations and measurements of processes at, or near active hydrothermal vents are only in initial stages of development. Under sponsorship of the University of Washington, however, a prototype system of a long-term ocean bottom observatory (LOBO) was designed, deployed, and recovered. Having succeeded with the initial experiment, efforts are now underway to more completely determine what kinds of in situ seafloor experiments will be required for the long term study of active ventfields.

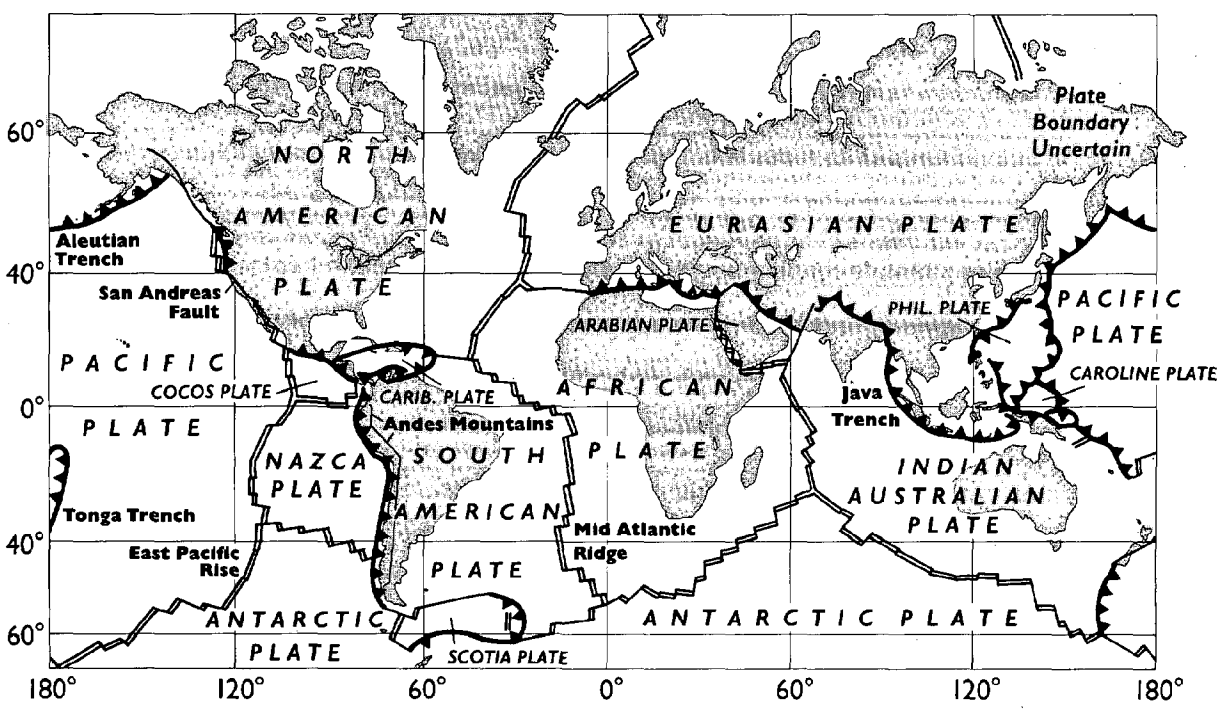


Figure 4 Global map of plate boundaries. Hot-water venting is concentrated in volcanic environments, principally along seafloor spreading centers (//). Other hot-water venting occurs in association with mid-plate, or hot-spot, volcanism and in volcanically heated backarc basins. Cold-water venting is associated with the subducting edges of plates (▲), primarily adjacent to continental margins.

The LOBO concept is important to RIDGEFLUX goals and therefore is a cornerstone to experimental plans. The NOAA/PMEL VENTS program is presently supporting development of a prototype chemical monitoring system which was successfully tested during the 1987 field program.

At present, the LOBO is viewed as basically a stationary system, although limited movement of some sensors using a manned submersible is planned. A new concept being explored jointly with National Bureau of Standards (NBS) and OAR (NURP and SG) is the development of an unmanned, untethered ROV incorporating artificial intelligence. A number of scenarios for such a device are being considered. Coordinated budget initiatives are being planned.

3.0 RIDGEFLUX Research Strategy

The NOAA/PMEL VENTS program, as outlined above, focuses on hydrothermal effects on the North Pacific basin and will serve as a foundation for the RIDGEFLUX Program and its global objectives. The VENTS program has shown that initial observational results should be followed by process oriented experiments designed to obtain quantitative limits and time series data on which predictive models can be developed. Consistent with this rationale, the principal thrust of RIDGEFLUX Program research is to quantitatively understand the effects of submarine hydrothermal venting from ridge systems on global ocean chemistry. Program objectives will be augmented by collaborative and cooperative research with other elements of NOAA, other agencies, and academic institutions with complementary programs.

Determination of the ridge-integrated hydrothermal signals necessary for addressing the RIDGEFLUX hypothesis, begins with a systematic inventory of the chemical and heat anomalies of the various vent field plumes along the ridge segments chosen for study and a characterization of the gross geologic features of those segments. Mapping of the plumes is particularly useful because the anomalies can be used to determine the integrated effect of hydrothermal venting on the water column over time scales that expand as the spatial scale of the observations expand. A promising new technique for determining the rate of dispersal of hydrothermal plumes has been proposed by Lupton and Craig (1981). They indicate that, by determining the scavenging rate of hydrothermal Mn in the water column, the variable Mn/^{3}He relationship may be used to provide an "internal clock" within advecting plumes. The development of such a unique tracer will be of major importance for the establishment of dispersal rates for hydrothermal emissions near active spreading centers.

In order to address the global consequences of ridge crest venting, research to establish relationships between the magnitude of hydrothermal emission signal and geological setting, as well as studies of the regional transport, loss rates, and temporal variability of hydrothermal emission products, will be conducted at distances ranging from meters to several hundred kilometers from active hydrothermal sources. The research tasks outlined below are referenced to three distance scales: "Near field" (<1 m to 1 km); "Mid-Field" (1 km to 100 km); and "Far-Field" (>100 km). In terms of the scale of features and processes being studies (e.g., vents, vent fields, ridge segments, entire ridges, and, at the largest scale, major ocean basins), this categorization is useful but somewhat arbitrary since the effects of hydrothermal venting are not rigidly bounded. Effects of hydrothermal venting observed at these spatial scales pertain to the variability of hydrothermal venting which occurs over periods of time ranging from minutes to millions of years. Variations in hydrothermal activity which occur over very short as well as very long time scales will be studied in an effort to converge on understanding hydrothermal processes which take place over the time interval of primary interest, i.e., interannual to centuries, and therefore contribute to our ability to predict change in the global ocean.

3.1 Far-Field (>100 km)

Regional chemical oceanographic anomalies, which appear to originate from spreading center hydrothermal sources on the Gorda/Juan de Fuca/Explorer ridge system, the East Pacific Rise, and, by reasonable assumption, from the MAR and other ridge systems as well, extend throughout large areas of surrounding ocean basins. The regional extent, age, and evolution of these anomalies will be determined by means of:

- Acoustic and other mapping techniques applied to ridge systems in ocean basins selected for study to determine anomalies indicative of venting,
- Water column chemistry surveys designed to reveal the regional extent of hydrothermal products and effects including heat, trace metals, SiO_2, He, and CO_2,

- Sediment coring to determine the type, quantity, and chronology of regional hydrothermal contributions to the sedimentary record.
- Determination of regional ocean currents to permit calculation of the heat and particulate fluxes within the hydrothermal plume,
- Synoptic CTD/transmissometer surveys to determine the geographic extent as well as the heat and particle loading in the hydrothermal plume.

3.2 Mid-Field (1 km to 100 km)

The axis of seafloor spreading centers is divided into morphologically discrete segments which apparently result from large-scale processes controlling magma supply to the crust (Francheteau and Ballard, 1983). Ridge segmentation is especially well developed along the Mid-Atlantic Ridge and the Gorda/Juan de Fuca/Explorer ridge system. Adjacent segments range in length from about 50 km to 100 km. These segments are bounded by structural discontinuities which often appear to mark boundaries between regions of contrasting volcanic, tectonic, and hydrothermal activity. Mid-field scale investigations that focus on regional contributions of hydrothermal emissions identified with discrete vent fields include:

- Acoustic, magnetic, and electrical mapping; geodetic surveys, supplemented by photography; thermal surveys (sediment heat flow and water column temperature); and sampling, to determine geological and geophysical factors which affect the location and size of active vents as well as their flow rates and the duration of active venting,
- Remote acoustic surveys augmented by photographic, transmissometer, and thermal surveys (sediment heat flow and water column temperature) to identify and map the regional extent of active hydrothermal activity,
- Determination of regional ocean currents to permit calculation of the flux of heat and particles carried within the hydrothermal plume.
- Synoptic CTD/transmissometer surveys to determine the geographic extent as well as the heat and particle loading in the hydrothermal plume,
- Discriminating the total hydrothermal source between discrete high-temperature and low-temperature sources,
- Chemical sampling and laboratory modeling to determine the chemical evolution and reaction rates of particulate and dissolved constituents of the plume,
- Determination of rates and mechanisms for precipitation (including biologically-mediated mechanisms) and dissolution of plume constituents through field and laboratory studies,
- Sediment coring to determine the duration, type, and amount of hydrothermal activity associated with specific vent fields and ridge segments,
- Numerical modeling to synthesize field observations into flux estimates.
- Correlation of regional tectonic history of the spreading center segments with stratigraphically preserved hydrothermal chronology.

3.3 Near-Field (1 km to 1 km)

Results of near field investigations of short-term hydrothermal events are required to establish the appropriate time and space scales for longer term sampling and measuring strategies. In order to achieve the intended results from the activities listed below, experiments will be conducted on the seafloor within vent sites for extended periods of time. During the next five years, the use of submersibles (and/or remotely operated vehicles) as well as surface ships will be required. Many mid-field-scale experiments will extend to the near-field as well; other near-field experiments include:

- Detailed geological mapping of target vent fields,
- Mineralogical, petrographic, and radiometric analyses of hydrothermal precipitates and host rock to determine the age and chemical history of venting on the scale of years to decades,
- Temporal studies of vent behavior including variations in temperature, flow rates, rates of accumulation and dissolution of hydrothermal precipitates, effluent chemistry, and correlation of these variations with geological controls,
- Collection of undiluted vent fluids from selected sites to determine undiluted, representative vent fluid chemistries which can then be compared between different vents, vent fields, segments, and ridges.
- Resolution of seawater/rock interactions at a range of extant temperatures using field and laboratory studies,
- Sampling of dissolved and particulate constituents within the buoyant plume at dilutions roughly between 1 and 1000 to establish the chemical evolutionary links between the undiluted and diluted plume.

Incorporation of the quantitative results from the above work will constitute the basis for, and even-

tual verification of, physical and chemical models for hydrothermal plume evolution. Physical models will include descriptions of the injection and dispersal of dissolved and particulate components of the plume based on geological setting, ocean currents, momentum and buoyancy fluxes, and entrainment of the hydrothermal plume into surrounding water. Chemical models will describe changing chemical components and reaction rates within the plume. These results will provide a quantitative look at the mechanisms and effects of submarine hydrothermal venting on the chemical evolution of significant portions of major ocean basins and will provide the framework for evaluating cause and effect links between hydrothermally produced variations in regional ocean chemistry and long term climate variations.

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Activities of RIDGEFLUX will be coordinated and linked to those of several other bureaus in NOAA, other agencies here and abroad, as well as the university community, and, where possible, private industry.

Within NOAA, NOS will provide ship support as research platforms and for aerial surveys. NURP will provide submersible and ROV support necessary to accomplish program goals. NSGCP will support research which complements and expands upon, RIDGEFLUX. For example, Sea Grant is currently supporting research in new instruments and concepts for long term and large scale measurements of processes at ridge crests; venting associated with hot spots; and cold temperature venting associated with subduction zones and the US/France Bilateral: preliminary discussions are underway for possible joint missions on the MAR, a probable field site for elements of RIDGEFLUX.

Interagency coordination: NSF continues to fund academic research proposals focused on ridgecrest and hydrothermal processes. Recently the NAS/NRC sponsored a national workshop to develop an NSF program. RIDGE, which if supported, will result in a long term academic ridgecrest research program. RIDGE has been specifically planned to integrate NOAA research which has the unique role in long term determination of oceanographic hydrothermal effects. Numerous academic researchers are involved in ongoing NOAA hydrothermal investigations. There also is a strong collaborative relationship between NOAA, the USGS and researchers from the Canada Geological Survey and Canadian universities focused on hydrothermal processes in the northeast Pacific.

Under established guidelines, MMS has organized a Gorda Ridge Task Force whose responsibility is to consider the possibilities for, and ramifications of, leasing portions of the Gorda for mineral exploration and mining. NOAA has a formal relationship with the MMS Gorda Ridge Task Force and several NOAA scientists have and are actively participating in collaborative Gorda Ridge research.

France continues to be very active both in the Atlantic and the Pacific. France has an ongoing and vigorous hydrothermal research program. Planning is now underway to have US/France ridgecrest collaboration in the Atlantic through the US/France Bilateral Agreement.

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In the 1960's, plate tectonics became a unifying theme and powerful hypothesis for testing the processes which govern the dynamic interaction of the global system of crustal plates. By the 1990's, seafloor processes will become an analogous unifying research theme which will serve to resolve longstanding questions concerning, for example, ocean chemistry budgets and long-term climate trends. Based on its ongoing leadership research position in hydrothermal research, its unique facilities and organizational elements and broad environmental mission, NOAA will play a key role in advancing ourunderstanding of venting and its connotations for predicting ocean climate.

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Baker, E.T., J.W. Lavelle, and G.J. Massoth (1985). Hydrothermal particle plumes over the southern Juan de Fuca ridge, *Nature* 316, 342-344.

Baker, E.T., and G.J. Massoth, (1986a). The along-strike distribution of hydrothermal activity on a spreading segment of the Juan de Fuca Ridge, *EOS* 67, 1027.

Baker, E.T.,.and G.J. Massoth (1986b). Hydrothermal plume measurements: A regional perspective, *Science* 23, 980-982.

Clarke, W.B., M.A. Beg, and H. Craig, (1969). Excess helium-3 in the sea: evidence for terrestrial primordial helium, *Earth Planet. Sci. Lett.* 6, 213-220.

Corliss, J.B., J. Dymond, L.I. Gordon, J.M. Edmond, R.P. von Herzen, R.D. Ballard, K. Green, D. Williams, A, Bainbridge, K. Crane, and T.H. van Andel, (1979). Submarine thermal springs on the Galapagos Ridge, *Science* 203, 1073-1083.

Edmond, J.M., (1981). Hydrothermal activity at mid-ocean Ridge axes, *Nature* 290, 87-88.

Edmond, J.M., C. Measures, R.E. McDuff, L.H. Chan, R. Collier, B. Grant, L.I. Gordon and J.B. Corliss (1979a). Ridge crest hydrothermal activity and the balances of the major elements in the ocean: The Galapagos data, *Earth Planet. Sci. Lett.* 46, 1-18.

Edmond, J.M., C. Measures, B. Mangum, B. Grant, F.R. Sclater, R. Collier, A. Hudson, L.I. Gordon and J.B. Corliss (1979b). On the formation of metal-rich deposits at Ridge Crests, *Earth Planet. Sci. Lett.* 46, 19-30.

Francheteau, J. and R.D. Ballard, (1983). The East Pacific Rise near 21°N, 13°N, and 20°S: inferences for along-strike variability of axial processes of the Mid-Ocean Ridge, *Earth Planet. Sci. Lett.* 64, 93-116.

Joyce, T.E., Warren, B.A., and L.D. Talley (1986). The geothermal heating of the abyssal subarctic Pacific Ocean, *Deep Sea Research* 33, 1003-1015.

Kasting, F., and S.M. Richardson (1985). Seafloor hydrothermal activity and spreading rates: the Eocene carbon dioxide greenhouse revisited, *Geochim. Cosmochim. Acta* 49, 2541-2544.

Kulm, L.D., E. Suess, J.C. Moore, B. Carson, B.T. Lewis, S.D. Ritger, D.C. Kadko, T.M. Thornburg, R.W. Embley, W.D. Rugh, G.J. Massoth, M.G. Langseth, G.R. Cochrane, and R.L. Scamman (1986). Oregon subduction zone: venting, fauna, and carbonates. *Science* 231, 561-566.

Langmuir, C.H., J.F. Bender, and R. Batiza (1986). Petrological and tectonic segmentation of the East Pacific Rise, 5°30′S-14°30′N, *Nature* 322, 422-429.

Leinen, M., (1984). Rates of hydrothermal sedimentation on the Juan de Fuca Ridge, *EOS* 65, 1112.

Lupton, J.E. and H. Craig (1981). A major helium-3 source at 15°S on the East Pacific Rise, *Science* 214, 13-18.

Lyle, M.W., Owen, R.W. and Leinen, M. (1986). History of hydrothermal sedimentation at the East Pacific Rise, 19°S, In: Leinen, M., Rea, D.K. e t al., Init. Repts. DSDP, 92: Washington, D.C., (U.S. Government Printing Office), 585-596.

Lyle, M. (1976). Estimation of hydrothermal manganese input to the oceans, *Geology* 4, 733-736.

Macdonald, K.C., R.M. Haymon, and L.J. Perram (1986). Thirteen new hydrothermal vent sites found on the East Pacific Rise, 20-21°S, *EOS* 67, 1232.

Massoth, G.J., E.T. Baker, J.P. Cowen, K.K. Roe, and P.Y. Appriou, (1985). The geochemical diversity of Juan de Fuca Ridge hydrothermal plumes, *EOS* 66, 929.

Metz, S., and J.H. Trefry (1985). Geochemistry of metalliferous sediment from the TAB hydrothermal field, Mid-Atlantic Ridge, *EOS, Trans. AGU*, v. 66., 936 pp.

Morton, J.L. and N.H. Sleep, (1985). A mid-ocean ridge thermal model: constraints on the volume of axial hydro thermal heat flux. *J. Geophys. Res.* 90, 11345-11353.

Nelsen, T.A., G.P. Klinkhammer, J.H. Trefry, and R.P. Trocine (1986/87). Real-time observation of dispersed hydrothermal plumes using nephelometry: examples from the Mid-Atlantic Ridge, *Earth and Planet. Sci. Lett.* 81, 245-752.

Nelson, T.A., G. Klinkhammer, and J. Trefry (1985). Real-time observation and tracking of hydrothermal plumes on the Mid-Atlantic Ridge, *EOS, Trans. AGU*, v. 66, 936 pp.

Owen, R.M. and D.K. Rea, (1985). Sea-floor hydrothermal activity links climate to tectonics: The Eocene carbon dioxide greenhouse, *Science* 227, 166-169.

Rea, D.K. and Leinen, M. (1986). Neogene controls on hydro thermal activity and paleoceanography of the southeast Pacific Ocean, In: Leinen, M., and Rea, D.K. *et al.*, Init. Rept. DSDP, Vol. 92: Washington, D.C. (U.S. Government Printing Office), 597-617.

Reid, J.L. (1982). Evidence of an effect of heat flux from the East Pacific Rise upon the characteristics of the mid-depth waters, *Geophys. Res. Lett.* 9, 381-384.

Rise Project Group (1980). East Pacific Rise: hot springs and geophysical experiments, *Science* 207, 1421-1444.

Riser, S.C., (1985). Maintainence and driving of helium-3 and thermal plumes in the abyssal South Pacific, *EOS* 66, 930.

Rona, P.A., G. Klinkhammer, T.A. Nelsen, J.H. Trefry, and H. Elderfield (1986). Black smokers, massive sulfides, and vent biota at the Mid-Atlantic Ridge, *Nature* 321, 33-37.

Sclater, J.G., C. Jaupart, and D. Galson, (1980). The heat flow through oceanic and continental crust and the heat loss of the earth, *Rev. Geophys. Space Phys.* 18, 269-311.

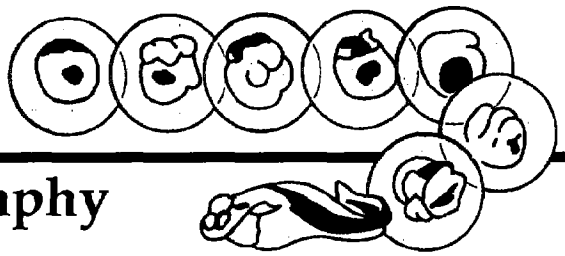
Stommel, H. (1982). Is the South Pacific helium-3 plume dynamically active? *Earth and Planet. Sci. Lett.* G1, G3-G7.

Thompson, G. (1983). Hydrothermal fluxes in the ocean, In: *Chemical Oceanography,* Vol. 8, J.P. Riley and G. Skirrow (eds) Academic Press, Condon., 272,337.

Von Damm, K.L., and J.L. Bischoff (in press) Chemistry of hydrothermal solutions from the southern Juan de Fuca ridge, *J. Geophys. Res.*

Chapter III

Fisheries Oceanography



Executive Summary

Problem and Opportunity

The fisheries resources of the United States are, with a few notable exceptions, products of coastal ocean waters and adjacent estuaries. These resources support the Nation's major commercial and marine recreational fishing industries. However, fish populations and communities fluctuate, sometimes substantially, from year-to-year and to even greater extents on longer intervals (interdecadally). This variability and lack of knowledge of its causes reduce the effectiveness of resource management and cause economic dislocations so characteristic to fisheries.

Research Strategy

A major goal of fisheries science is the accurate prediction of the status of species for both short-term (inter and intra-annual) and long-term (interdecadal) time periods. Most of the existing forecasting methods are known to be inadequate, particularly in regard to long time scales and radical population change. Short-term predictions are needed to better set harvesting levels and conditions (timing, place, etc.). Long-term predictions are essential in identifying the booms, collapses, and changes in community structure that cause the major dislocations in fisheries. Recruitment is the process by which young fish (or shellfish) are added to the adult or fished stock, and is, therefore, the essential process on which the continuity of a fishery depends. Evidence to date suggests that recruitment variability is intimately linked to the physical dynamics of the oceans and large-scale climatic fluctuations. Fisheries scientists throughout the world have identified recruitment fisheries oceanography as the most important topic in fisheries science, and the key to accurate predictions.

A research program on fisheries recruitment not only has the potential for improving fisheries management responsibilities, but also for improving man's understanding of the linkages between the physical environment and the ocean's productivity.

Recruitment fisheries oceanography needs to address the following list of questions:

- *What is the role of a biotic environmental variation in controlling survival of eggs, larvae, and juveniles?*
- *What is the role of food availability in controlling survival of larvae and juveniles?*
- *What is the role of invertebrate and vertebrate predation in controlling survival of eggs, larvae, and juveniles?*
- *What is the role of physical factors in transporting eggs or larvae to appropriate juvenile habitats or in controlling predator-prey interactions?*
- *How do the above factors interact to affect total survival to recruitment?*
- *Does the relative importance of various survival mechanisms change within or among years?*

There is general agreement among researchers that the program should focus equally on short- and long-term time scales, seek to determine factors promoting survival rather than accounting various sources of

mortality, and focus on comparing recruitment processes in a limited number of target coastal ocean environments (upwelling, fronts, continental shelf/banks, and large lakes).

Why Now?

Since the initiation of the Exclusive Economic Zone and its concomitant fisheries management responsibilities, fisheries oceanography has become a high priority. The first requisite of effective fisheries management, a way to accurately forecast stock size, is not available. Existing forecasting methods have been criticized for being inaccurate, unrealistic, oversimplified, and biased towards over-representing the effects of fishing.

Benefits

As a result of the activities in the research strategy, it should be possible to identify and efficiently monitor the environmental factors that are the best predictors of stock abundances. Improved understanding of the causes of population size and variability will enable the consequences of man's activities in coastal and marine environments to be evaluated. Such research should also lead to the prediction of major climate and oceanographic events since it has recently been demonstrated that movement, distribution, and variation in recruitment of marine organisms are early indicators of such events. When we gain an understanding of the factors that control the size of fish and shellfish populations, it will be possible to determine how the actions of man affect these populations.

1.0 Introduction

A major goal of fisheries research is to provide a scientific basis to develop the capability to manage fisheries for maximum yield in inherently variable physical, biological, and sociological environments. Where possible, prediction of both interannual and long-term variability in resource production is highly desirable. Even in cases when prediction is not attainable, fisheries scientists can assist management by partitioning the variation in resource production into understandable components (e.g., that variability caused by the physical dynamics of the ocean, biotic interactions, and large-scale climatic fluctuations). In order to satisfy short-term management demands, it is important to understand inter-annual variability. In some fisheries this may be accomplished by simply indexing pre-recruit year class abundances through direct stock assessment methodologies. But this technique is generally unreliable, still, most significant changes in fisheries production seem to occur on a much longer time scale (e.g., interdecadal). These are the blooms, collapses, and major changes in community structure and species composition that cause significant dislocations in fisheries (e.g., sardine-anchovy in eastern boundary current ecosystems, gadoid-flatfish-crustacean dynamics in continental shelf ecosystems). The goal of recruitment research is to improve our understanding of fish population dynamics on both of these time scales and so assist management, the fishing industry, and the public.

Recruitment is the process by which young fish (or shellfish) are added to the adult or fished stock. Research in fisheries during the past 5 to15 years provides substantial evidence that major fluctuations in populations of fish and shellfish are often caused by variable survival rates among early stages of these organisms. Survival prior to recruitment has generally been identified as the single most important process influencing the dynamics of commercially important fish and shellfish populations (Steele *et al.*, 1980). Simply stated, recruitment variability, which is an outcome of variable larval and juvenile mortality, is presently considered the central problem of fisheries science.

Although elements of fisheries recruitment processes have been studied for many years, only during the past 5 years has the topic been identified within NOAA as a high priority area of research. In part, this is related to NOAA's fisheries management responsibilities in the Exclusive Economic Zone (EEZ). The first requisite of effective fisheries management is the ability to effectively estimate or forecast stock size. Many existing forecasting methods are inadequate particularly in regard to long time scales and radical population change. A major criticism of most current approaches is that they are inherently unrealistic, eliminating complexity by over-integrating the effects of many perturbing factors and/or over-

emphasizing the effects offishing. For example, in most fishery yield models, recruitment is represented as a pure density-dependent deterministic function of the size of the spawning stock, and fishing itself is the major controlling factor instock dynamics. Further, current fishery management theory is based on assumptions of steady state or equilibrium processes. Empirical evidence simply does not bear this out (Francis *et al.*, 1987).

If our marine fisheries resources are to be wisely managed, we need to establish an integrated national program of fundamental recruitment research. In addition to its practical management applications, this research has intrinsic scientific merit. Recruitment research requires integrating the biotic system with the abiotic (ocean and atmospheric) environment. The importance of these linkages differs among species and ecosystems; however, particularly in the context of global change it is essential to our understanding of the ocean system and its dynamics that these processes be studied.

2.0 Mechanisms Controlling Recruitment

A number of hypotheses on the mechanisms that control recruitment of larval and juvenile fishes have been suggested. These mechanisms include both abiotic factors such as changes in temperature, salinity, or local circulation, and biotic factors such as food availability or the presence of predators. While each of these factors could act alone and affect larval and juvenile survival, most likely it is their interactions that control year class strength. In the past, much research has focused on elaborating evidence to support one of these mechanisms (e.g., starvation, predation, or advection). If in fact they interact, these mechanisms cannot be considered as independent, alternate, or competing hypotheses. These factors are integrated in the growth dynamics of larvae and the size or growth rate-dependence of predation and other direct sources of mortality. We need to address more clearly how these potential mechanisms interact and how we can evaluate these interactions. Recent studies at the Northeast Fisheries Center have been directed toward determining the effects of interactions of temperature, prey abundance, and predation on haddock recruitment (Laurence 1985, Lough 1985, and Cohen *et al.*, 1985).

2.1 Starvation Hypothesis

One of the best known hypotheses has been referred to as the starvation hypothesis. This hypothesis is based on the observation that the average density of food items for larval fish in the sea is low compared to their requirements for growth and survival. Further, small marine fish larvae are extremely vulnerable to these low food levels; many small larvae have only a few days from first possible feeding to their point of no return (irreversible starvation). When oceanic conditions are stable, aggregations of food apparently supply sufficient energy for growth. But turbulence due to storms and other physical variability can disrupt these patches leading to reduced growth rates of larvae, and in the extreme case, starvation. First feeding larvae seem to be particularly vulnerable to starvation, but the entire larval stage seems to depend upon ample food to maintain high growth rates.

A second hypothesis, the predation hypothesis, is based on the observation that eggs and larval fishes are consumed by a wide variety of invertebrate and vertebrate predators. Copepods, salps, jellyfish, chaetognaths and a variety of other invertebrates have been shown to eat eggs and yolk sac larvae in the laboratory. Fishes, including adult conspecifics, actively consume larvae and juveniles in laboratory experiments. Unfortunately, few of these experiments have examined the importance of predation on larvae when alternate prey are available. Field evidence of predators occupying the same water masses as eggs and larvae is available as is some diet data to suggest that fishes, in particular, do consume eggs and larvae in the field. A major problem with the field diet data are that eggs and larvae are extremely ephemeral in the stomachs of predators, so the effects of predation are difficult to document from field samples.

A third hypothesis states that advection processes and other factors controlling larval transport can have marked effects on larval survival by transporting larval towards or away from appropriate habitats. When environmental conditions favor transport to appropriate "nursery areas," growth and survival may well be high. Physical oceanographic processes related to larval transport are potentially very important to recruitment success.

A fourth hypothesis, developed at the Northeast Fisheries Center, argues that recruitment is determined largely by predation on post-larval fish by other fish (Cohen and Grosslein 1982).

2.2 Problems with Alternative Hypotheses

One problem with traditional thinking is that these mechanisms are not truly "alternatives." Both environmental factors (e.g., temperature, salinity) and the availability of appropriate food affect larval fish bioenergetics and growth. In larval and juvenile fishes, all surplus power (energy per time, Ware 1982) is allocated to growth, so when environmental factors or food vary, larval growth rates will vary. The starvation hypothesis only explains the extreme case when the energy balance remains negative long enough for the fish to die.

Predation on young fish is also influenced by both nutrition and growth. Firstly, there is evidence to show that starving larvae or larvae receiving lower rations swim more slowly and are more vulnerable to predators. Secondly, predation is often size dependent. If growth rates in larvae are reduced, they are exposed to gape-limited predators for a longer period of time (Werner and Gilliam 1984). One can also imagine situations where the converse is true depending on the predator field.

Virtually no evidence is available to support the hypotheses that advection per se is a major source of mortality. Eggs and larvae may be advected to areas in which conditions are less suitable for normal development or growth. The causes of mortality are identical to those attributed to the starvation hypotheses. In short, factors that influence larval growth dynamics cannot be considered to be independent, because they are integrated in the growth bioenergetics of the larvae. Because risk of predation depends on prey size, predation cannot be considered as a separate factor. Larval transport cannot so readily be integrated into the growth dynamics framework. Larvae and juveniles which are transported to an inappropriate habitat may have less food or higher energetic costs or a higher risk of predation, but the critical issue is that they failed to reach a critical habitat required to successfully complete their life history.

In order to progress more rapidly toward understanding recruitment, mechanisms which were formerly considered to be the bases of alternative hypotheses must be integrated. Fish which recruit to the fishery are the survivors of various interacting mortality mechanisms. One can invoke a variety of mechanisms to explain why 99+ percent of the eggs and larvae die *or* one can focus on the unique characteristics of survivors which allowed them to succeed where so many others had failed. Although research on the causes of high mortality rates among young stages of fish and shellfish must continue, future analyses might more profitably focus on the unique features of survivors rather than on estimating mortality rates or explaining how the larvae may have died.

Studies of recruitment in fishes must consider the effects of microscale and mesoscale environmental variation on the abiotic and biotic factors which together influence growth dynamics of the larvae. They must also obtain information on the density and size structure of the predator fields to which the larvae are exposed. Last they cannot neglect detailed physical oceanographic, meteorologic, and climatic information to address the issue of larval and juvenile transport, and to explore the fundamental causes of long-term ecosystem change.

3.0 Research Issues in the Recruitment Dynamics of Fish and Shellfish

The major questions of relevance to recruitment in fish and shellfish address the effects of changes in abiotic or biotic factors on variations in spawning activity and on the survival of eggs, larvae, and juveniles. How does environmental variation influence spawning activity of pelagic marine fishes? What factors control survival of eggs, larvae, and juvenile fishes? Much recruitment research has been based on the notion that adult stock size has little influence upon recruitment except when stocks are extremely low. Intraseasonal spawning activity in adults might well be responsive to environmental variation; this issue cannot be neglected.

The following list of related questions concerns factors considered central to recruitment dynamics of fishes. The list is neither exhaustive nor mutually exclusive.

- What is the role of abiotic environmental variation in controlling survival of eggs, larvae, and juveniles?
- What is the role of food availability in controlling survival of larvae and juveniles?
- What is the role of invertebrate and vertebrate predation in controlling survival of eggs, larvae, and juveniles?
- What is the role of physical factors in transporting eggs or larvae to appropriate juvenile habitats or in controlling predator-prey interactions?
- How do the above factors interact to affect total survival to recruitment?

- Does the relative importance of various survival mechanisms change within or among years?

The most effective means to answer these questions is to emphasize the interactions among the various potential recruitment mechanisms and to focus on characteristics of the survivors to the age at which year-class strength is established.

3.1 Recruitment Mechanisms Spatial and Temporal Scales

Recruitment dynamics can be examined at a variety of spatial and temporal scales. Appropriate scaling requires a clear understanding of relevant physical oceanographic processes which 1) create and maintain a favorable habitat to be occupied by eggs, larvae, and juvenile fish and shellfish during the recruitment period; 2) influence egg or larval transport to anappropriate nursery habitat; 3) serve as migration routes for juveniles to appropriate nursery areas; or 4) attract or concentrate predators.

This suggests that one appropriate time scale over which to explore recruitment mechanisms is short-term (e.g., intra-annual). Studies of intra-annual dynamics and larval survival mechanisms provide insights as to which portion of the spawned cohort accounts for the bulk of the survivors rather than simply estimating the time course of mortality. The suggested focus is on how and why survivors differ from the average fish spawned and whether survivors possess any unique characteristics or co-occur with critical oceanographic conditions which correlate with their success. Characteristics of the survivors provide useful information to interpret how the interacting constraints on successful recruitment behave and allow us to screen among the potentially important recruitment mechanisms that determine which individuals survive from a spawned cohort.

Climatic fluctuations and their subsequent oceanic effects are becoming recognized as important phenomena affecting major long-term shifts in marine fisheries production. Figure 1 shows an 80-year time series of variations in estimated abundance of three stocks of sardine, one each in the Northwest Pacific, Southeast Pacific, and Northeast Pacific. This figure suggests a relationship between climate-ocean (over relatively long periods of time) process, and the status of fish populations that reside within the subtropical transition zones of the Pacific Ocean basin. Figure 2 shows evidence of a direct correlation between interdecadal climate fluctuations and fish production–in this case, Bristol Bay (Alaska) sockeye

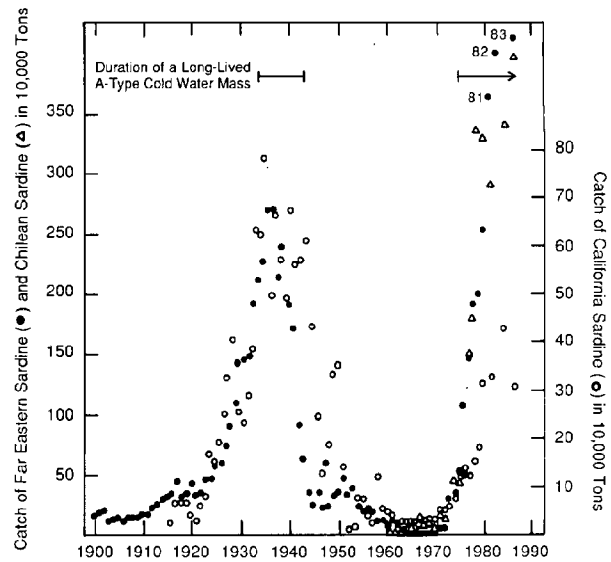


Figure 1 Large-scale variations in catch of three species of sardine (Far Eastern, Californian and Chilean).

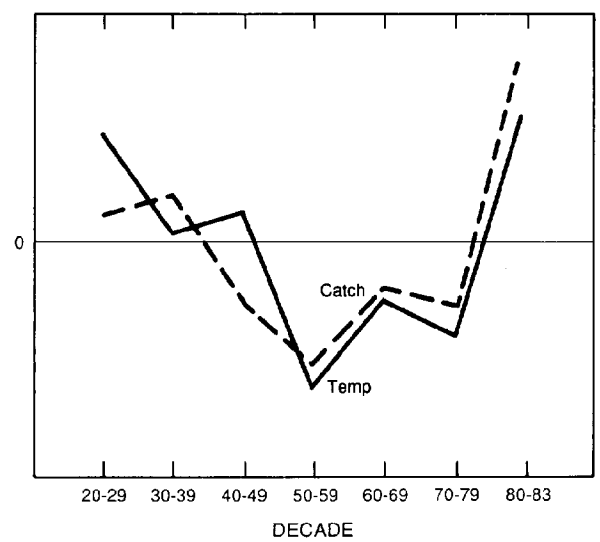


Figure 2 Ten year mean Bristol Bay winter (Nov.-Mar.) air temperature anomalies and Bristol Bay sockeye catch anomalies (standardized – (obs-mean/std)).

salmon. Similar relationships have been shown for other commercially important Bering Seastocks. Debates have been raised for years over the relative impacts of exploitation and environment on major shifts in fisheries (e.g., California sardine, Bering Sea king crab, North Sea gadoids). It seems clear that major fishery resource collapses often occur at times of intense fishing. However, causality does not necessarily follow.

Therefore, major questions that need to be asked with respect to long-term (interdecadal) shifts in fishery production include:

- How are large-scale atmospheric and oceanic processes linked to major changes in fish community structure?
- Does the exploitation process itself affect major changes in fish community structure and under what circumstances?
- Are community shifts primarily due to responses of individual populations to environmental change or are more subtle food web interactions important?

The answers to these long-term (interdecadal) questions most likely will require a more broad-based approach to examining marine ecosystem dynamics than the answers to the short-term (interannual) questions. Studies of long-term dynamics will focus on such things as community structure, changes in spatial and temporal dynamics, food web structure and how they are affected by both global weather/circulation processes and resource harvesting strategies. Of utmost importance, however, is that these studies be driven by specific hypotheses rather than an intuitive longing for a full and complete ecosystem characterization. The latter approach is both inherently and practically infeasible except in very restricted circumstances.

It is unclear how the processes and mechanisms critical to intra-annual recruitment dynamics are coupled to those determining long-term shifts in fish community composition. Understanding the recruitment mechanisms relevant to both of these time scales is, however, critical to successful fisheries management.

4.0 Why Now?

Fishery scientists have never been in a better position to study the factors affecting recruitment than they are today. In the last 25 years, an enormous fund of information on the biology of commercially and recreationally important fish species has accumulated. Concurrently, new methods of studying them have been perfected. In particular, we have become especially knowledgeable about the seasonality of spawning, egg production, spawning frequency, biomass fluctuation, and early development of a number of important fishes (e.g., the clupeiform species–the anchovy, the sardine, the menhaden, the herring, and the gadoids). Studies of the early life history of fishes have advanced greatly in recent years, specific hypotheses on the respective roles of fish eggs, larvae, and juveniles in variable recruitment and population fluctuation can now be examined in the field and in thelaboratory. Advances have similarly been made in biological and physical oceanography and these can and should be applied to fisheries problems. Last, emphasis on recruitment research within NOAA is consistent with the national and international focus on the biological implications of global weather and climate change.

4.1 Scientific Investigations Underway

Various NOAA researchers have been integrally involved in developing the scientific background upon which much current and proposed recruitment research is based. Studies relevant to recruitment dynamics have been conducted under the auspices of NMFS, OAR, (including both ERL, Sea Grant, and NURP (National Undersea Research Program)) and other NOAA agencies. These studies provide a demonstrated commitment to cooperation among fisheries biologists, oceanographers, meteorologists, and ecologists in NOAA to address the complexities of recruitment dynamics. Approaches have included field surveys of eggs and larvae and larval food in concert with detailed physical oceanographic research, laboratory experimentation to explore particular mechanisms and mathematical modeling. One of the major ongoing NOAA efforts in recruitment fisheries oceanography is the Fisheries Oceanography Coordinated Investigations (FOCI). This is a joint ERL/NMFS project to study larval recruitment into the walleye pollock fishery of the western Gulf of Alaska. Critical aspects of the physical environment under investigation are the temporal and spatial behavior of wind-driven currents, the Alaska Coastal Current and slope/shelf exchange. Biological research focuses on the major sources of mortality of eggs, larvae, and juveniles and how these are influenced by oceanographic conditions, egg quality, larval and juvenile food resources and predator interactions. The study employs advanced technology in conduct-

ing detailed biological and physical field sampling as well as historical satellite imagery to relate physical environmental variation to recruitment success.

An earlier ERL/NMFS cooperative project, conducted between 1978 and 1982 was an investigation of the relation between the physical features of the Mississippi River Plume and the feeding growth and survival of larvae of several economically important species. This project focused on the biological importance of the Mississippi River front rather than larval transport and currents.

The NMFS Georges Bank Ecosystem study contains a recruitment research program on the groundfish community of the Bank. Findings to date indicate that most fish biomass produced is consumed by the fish themselves (i.e., predator-controlled community). Also noted, is that fish biomass remains constant but species composition can change drastically. Combined laboratory and field experiments provided evidence which suggests that interannual recruitment variability in cod results from variable predation rates on juveniles. The longer term species shifts noted also appear to be related to predation in concert with undefined environmental conditions that seem to confer a competitive advantage to one or more species.

A long-term joint state and NMFS research project on the California Current Upwelling System (CalCOFI) has led to a proposed comparative project on the four major Eastern Boundary Current Systems–Peru, Canary, Benguela, and California–in collaboration with the Intergovernmental Oceanographic Commission (Sardine Anchovy Recruitment Program–SARP). This project seeks to develop important linkages between the physical features of these systems and recruitment dynamics. The project uses the most advanced techniques to examine the details of intra-annual recruitment mechanisms (Methot, 1983). One of the strengths of this and other NOAA programs (e.g., the Georges Bank Ecosystem) is the combination of field sampling, laboratory experimentation and mathematical modeling employed.

To date, Sea Grant-sponsored academic research has focused on various individual processes integral to recruitment success–trophodynamics of larvalfish and shellfish, transport of larvae to appropriate nursery areas and predator-prey relationships among early life stages. Rice *et al.*, 1987, was able to demonstrate that growth rate, which integrates the physical and nutritional environment, is strongly correlated to survival among fishes. Research on the recruitment of blue crab (McConaugha 1983) and spot and croaker (Petrafesa *et al.*, 1986) have shown that among the so called "estuarine dependent" species, the transport of larvae and juvenile stages from offshore to "nursery areas" is critically important to recruitment of these species. Brewer *et al.*, 1984, were among the first scientists to show in field studies that plankton organisms are potentially formidable predators on young fish. Recent studies on survival of juvenile salmon (Pearcy, personal communication) provided information suggesting that salmon recruitment was intimately related to predator concentrations at the mouth of spawning rivers. Most Sea Grant investigations have emphasized experimental biology with limited emphasis on oceanographic conditions or long-term field efforts.

4.2 Technical Advances

Pioneering work by Methot (1983), an NMFS researcher, used otolith analysis to examine the birthdate frequency distribution of northern anchovy larvae caught in the CalCOFI surveys to that of survivors caught in the fishery at age 1+. He found that harvests were drawn disproportionately from only a portion of the spawning season. By comparing the intra-annual patterns of recruitment success, one can identify periods of disproportionate mortality or exceptional survival. These periods can then be correlated with short-term abiotic or biotic events, which may influence survival, to more tightly link cause and effect. This approach has also been successfully applied to examine the effects of abiotic and biotic factors on growth and relative survival of larval and juvenile American shad (Crecco and Savoy 1985) and to relate survival and recruitment success of Lake Michigan bloater to their growth dynamics (Rice *et al.*, 1987). The power of this approach is that it focuses on the unique characteristics of survivors and suggests hypotheses regarding specific recruitment mechanisms which can subsequently be tested either experimentally or via designed observations. Over the past decade, our capacity to physically sample the ocean environment has been radically enhanced. Fundamental understanding of upper ocean dynamics requires current measurements. Acoustic doppler based methods for doing this have been recently emphasized. Because these permit real-time characterization of the entire upper water column, the data are particularly suitable for interdisciplinary biological/physical sampling studies.

Conductivity/temperature/depth (CTD) technology has also rapidly advanced and CTD's are now commonly incorporated into biological oceanographic

samplers. Instrumented buoys are becoming common and can yield both hydrographic and meteorological data over time/space scales impossible to achieve with shipboard sampling (e.g., see Weller and Davis 1980). The combination of satellite altimetry, advanced high-resolution radiometer (AVHRR) and scatterometry imply that meteorological and physical coupling may be observed in near real time over global scales. New methods of biological oceanographic sampling (reviewed in Ortner *et al.*, 1981 and Dicky 1988) employing acoustics, bio-optics, satellites, telemetry and pattern recognition provide a basis for developing new and powerful tools for quantitatively sampling larval and juvenile marine fish andtheir food resources. Both *in situ* and remote sensing have inherent advantages and disadvantages (e.g., see Esias 1981) but there is no doubt satellites are fast becoming indispensable tools in the field of fisheries oceanography (Anon 1981). A critical attribute of the newest biological oceanographic samplers is that they make it possible to obtain biological data on time and space scales comparable to available physical data. Combining this with real-time feedback will be essential to addressing physical-biological coupling. Such feedback is also essential to progress in utilizing artificial intelligence techniques to control sampling. These advances are required to adequately sample comparatively rare organisms like juvenile fish.

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A growing recognition of the urgency of describing and understanding the central role of the ocean in global change and the multiple effects of the ocean upon our society have stimulated interagency strategic planning. This is reflected in the recently released U.S. Global Ocean Science Program (GOSP). One of the principal complements, and one for which a major role for NOAA is forecast, is Global Ecosystems and Productivity Processes. Even in the short-term, it is felt that NOAA can and ought to specifically direct effort toward support of Fisheries Oceanography. Given NOAA's organizational character, this role is both appropriate and realistic. Failure to exploit this opportunity will result in a loss of research momentum, and could deprive society of information needed to wisely manage marine fisheries into the 21st century.

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Since the implementation of the Magnuson Fisheries Conservation and Management Act of 1977, the federal government has had a major role in the assessment and management of the fishery resources of the EEZ. NOAA, as the designated fisheries agency and the nation's lead civilian ocean science agency, not only is obligated but is uniquely qualified to pursue a research program to increase understanding of recruitment.

NOAA's diverse capabilities in fisheries science and management, biological oceanography, physical oceanography, meteorology, and computer modeling provide a pool of expertise capable of addressing major recruitment problems in a comprehensive manner.

- NOAA's organization infrastructure including mission-oriented components (NMFS), fundamental research components (ERL), academic granting programs (Sea Grant), and support groups (NOS) make NOAA the logical agency for implementing such a broad-based and comprehensive program.
- NOAA has a national network of marine fisheries and oceanographic research facilities that includes–NOAA ERL and NMFS laboratories, Sea Grant programs and several NOAA/academic cooperative institutes.
- NOAA scientists have excellent relationships with scientists in academia and state agencies. These relationships promote collaborations among scientists interested in recruitment in NOAA, the academic community, and the states. The partnerships between NOAA and academia can be used efficiently to respond to complementary needs for both long-term and short-term recruitment research.
- NOAA is sensitive to resource management needs. In partnership with the states, NOAA is responsible for managing the living marine resources of the EEZ.

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The NOAA recruitment research program will focus on the mechanisms that control the survival of larval and juvenile fish and shellfish both on the short-term (intra-annual) and long-term (interdecadal). The ultimate goal is to develop an understanding of the recruitment process directed toward achiev-

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ing the capability of predicting fish productivity (quality and quantity) in the context of abiotic and biotic change.

The research program will focus on comparing recruitment processes of a limited number of species in a limited number of target marine ecosystems (upwelling systems, riverine and pelagic fronts, shelf systems, and large lakes) which offers an alternative to previous studies that have attempted comprehensive examinations of single marine ecosystems. This comparative approach will lead to a more generic understanding of recruitment processes (Bakun 1985).

Specifically, the approach:

- systematizes fragmentary information and insights in order to foster useful generalities concerning physical, biological, and human impacts on fisheries production,
- overcomes problems associated with the complexity and heterogeneity of marine ecosystems by studying only specific system attributes and parameters,
- reduces the overall effort needed by focusing on similarities among ecosystems instead of the uniqueness of individual systems,
- improves the chance of detection of specious relationships,
- increases confidence in weak relationships, and,
- is most informative in situations not amenable to controlled experiments.

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The most promising of the approaches is to investigate intra-annual recruitment mechanisms by documenting the unique characteristics of the survivors relative to the average fish (Methot 1983, Crecco and Savoy 1985, Rice *et al.*, 1987). This requires field sampling to collect the species of interest at different stages of development throughout the spawning season. In order to track a cohort, detailed understanding of fish movements relative to the physical circulation is absolutely required. Given this physical constraint, one can use otolith analysis to compare the birth-date frequency distribution and daily growth trajectory of the survivors at any point in the life history to fish sampled earlier.

The null hypothesis is that the survivors are drawn at random from the spawning distribution. In practice, if the null hypothesis cannot be rejected, then there is no point to look for particular mechanisms contributing to exceptional mortality or survival. If the null hypothesis is rejected, the survivors are shown to differ in some way (birth dates, growth rates, appearance of low ration checks on the otolith c.f. Rice *et al.*, 1987) from the average fish which did not survive. These differences reflect the interaction of the various sources of mortality and the patterns should suggest the factors which allowed particular larvae to be successful (e.g., first fed when food was seasonally most abundant and/or available, grew exceptionally rapidly in the first week of life, hatched during a period favorable for transport to an appropriate nursery habitat, hatched after important predators on larvae moved to another habitat).

The characteristics associated with successful recruits should allow the researchers to reject some recruitment mechanisms and to focus further research in that system. Tighter recruitment hypotheses can then be proposed which can be tested in laboratory or field mesocosm scale experiments or via specific field observations.

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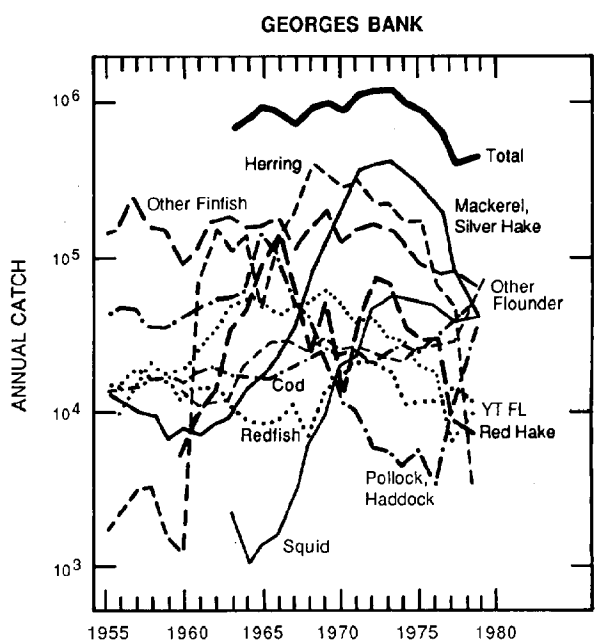
As was mentioned earlier, the most significant changes in fisheries production seem to occur relatively infrequently, and are the changes that cause major dislocations in fisheries. Because they occur on such a long time scale (e.g., interdecadal), they have proven to be most difficult to study (Figure 3).

Figure 3 Annual catch (total and by species) for Georges Bank (after Hennemuth, 1979).



Any serious study of long-term changes in resource production requires careful analyses of records of the past. These changes have been hypothesized to be strongly influenced by changes in oceanic variables which in turn are often significantly affected by fluctuations in the atmosphere (Wooster 1983). Therefore, a combination of biological, oceanic, and climatic records of the past must be studied and linked. The work of Koslow *et al.* (1987) and Hollowed *et al.* (1987) use fishery records of the past to explore long-term resource dynamics. Boehlert and Yoklavich (1986) use otoliths of long-lived species to develop long-term growth records. A critical factor in any analyses attempting to link long-term atmosphere and ocean environmental variability with fishery resource production is the linking of time and space scales upon which climatic changes occur to those upon which fish population and community changes occur. The work of Smith (1978) and Bakun (1983) address this issue and suggest ways that these problems might be scientifically addressed. These basic scientific questions are multifaceted: statistical, biological, and physical. If the recruitment problem is to be significantly addressed, major breakthroughs in the study of long-term environmental-biological linkages must be made.

Long-term changes in the relative abundance of stocks within a fish community could not only relate to long-term climatic variability but to species interactions. The key question is whether community changes are due to independent population responses to environmental change (autecology) or whether some of the changes relate to species interactions (synecology). Improved understanding of the mechanisms behind recruitment dynamics of particular species are very useful if species interactions are unimportant. But, mechanisms that are important to single species on an intra-annual (short-term) basis may or may not be the same mechanisms responsible to long-term changes in a population's abundance. Even if species interactions are important, environmental factors may contribute to the shifts. If environmental changes alter the abundance of particular species, the whole community may then shift due to interactions (e.g., Paine 1980) between this species and the others in the community.

Recent progress in our understanding of food webs suggests that there area number of ways to examine any particular web and the interactions among its components. The first and oldest view is the connectance web, which focuses on all the trophic connections among food web components. This way of viewing webs requires a detailed understanding of diets of each fish species throughout its ontogeny. A second way of examining food webs is to weight food web connections by rates of energy or material flows. This is the classical "ecosystem approach" and often focuses more on materials or energy than the qualitative characteristics of food web components (such as what species occupies a particular niche). In terms of fisheries, which species is abundant as the major piscivore or planktivore, for example, is often of great management importance. A third way of looking at food webs is to examine food web linkages and look at the strength of species interactions or food web connections (Paine 1980). In this approach, the emphasis is on the "strong interactions" in the food web rather than on all possible interactions. The data from a number of food webs suggest that the number of strong interactors is much lower than the total number of interactions. If the strong interactors can be identified, then community changeovers become more predictable. In many aquatic systems, piscivorous fishes are relatively unimportant from the perspective of total food web connections or energy flow, but in aquatic systems, they have been shown to have a profound impact on food web structure and function (Kerfoot and Sih 1987, Carpenter 1988). Top piscivores are thus often strong interactors. To date, the only way to prove whether a particular species is a strong or weak interactor is to conduct controlled experiments. This is difficult to do in the pelagic, but environmental variation and exploitation are more-or-less constantly performing experiments that fisheries biologists may be able to take advantage of if they pursue hypothesis-oriented field-studies.

If we are to understand the processes that control long-term recruitment dynamics and community change, we will need to understand both climate-population recruitment relationships and species interactions. This is a formidable task that may require different methods than those that have proven useful in understanding intraseasonal dynamics.

7.0 Target Marine Ecosystems

Continued progress toward understanding recruitment will then depend upon the development of conceptual models of the recruitment process and the explicit use of the comparative approach upon representative fisheries in diverse oceanographic systems. Though systems differ dramatically in their basic oceanography and species composition, the same general set of processes control recruitment. By

comparing within and among oceanographic/ fisheries systems and across species of larvae, we may be able to derive some generalizations regarding the interaction of mechanisms controlling the recruitment process.

7.1 Upwelling Systems

The four major Eastern Boundary Current systems, the California, Peru, Canary, and Benguela Currents are characterized by very similar environmental changes, e.g., intense seasonal upwelling. These regions contain very similar, recurrent groups of marine fishes and other organisms. This is particularly striking when one considers the species composition of the fish fauna; each Current is dominated by a sardine, an anchovy, a hake, a jack mackerel, a scombroid mackerel, and a squid. Many of the major fisheries in the world are located in these regions presumably because of enhanced availability of food to fish and shellfish larvae, juveniles, and adult fishes due to stimulation of primary and secondary production.

Upwelling is also a characteristic of water movement along the shore at headlands. The Kuroshio Current impinging on Japan is an excellent example of a current which produces this effect. Sardines, anchovies, and other commercial fish and invertebrates common to upwelling systems also abound there.

7.2 Fronts

Fronts, defined as zones of discontinuity that separate water masses, are receiving increasing attention from fishery biologists. Because these features provide horizontal structure they affect the spatial distribution of organisms of fishery importance as well as the distribution of food organisms and predators. A growing body of information indicates that fishes, their larval forms, and their zooplanktonic food and predators may be aggregated along frontal zones. As a result of this aggregation, it is likely that the factors most influential to recruitment success operate along frontal zones and may affect the greatest proportion of an annual year class. Aggregationis affected by frontal convergence, whereas frontal divergence could disperse organisms. Fronts are often dynamic, and their movement can displace or disrupt existing distributions of fishes, fish larvae, and zooplankton. Both oceanic and estuarine fronts have major influences on recruitment dynamics in major U.S. fisheries. Oceanic frontal zones (e.g., Gulf Stream) can influence the spatial distribution of spawning, as well as larval stages, food resources and predators of pelagic fish species. In addition, these fronts may provide the hydrodynamic mechanism that affects successful transport of pre-recruits to their nursery areas. Estuarine fronts (e.g., Mississippi and Columbia River plumes) have major impacts on both economically important species with a life history strategy wherein spawning is offshore but nursery areas are in estuaries (e.g., menhaden, spot, redfish, summer and white flounder) and salmonid fish that spend critical juvenile life history stages near frontal boundaries. In these cases, the links between physical and biological processes are likely to be both especially significant and amenable to analysis.

7.3 Continental Shelf/Bank Systems

Continental shelf areas contain some of the most productive waters on the globe. Within these, some of the world's largest and most valuable groundfish and invertebrate fisheries take place. Two distinct types of these systems are shallow shelves directly associated with a continental land mass (e.g., E. Bering Sea shelf) and shallow banks totally surrounded by ocean water masses (e.g., Georges Bank). Production in the former tends to be associated with physical conditions which allow for transport of eggs and larvae to appropriate habitats. In the latter, production seems to be more dependent on stable local gyres which prevent dispersal of eggs and larvae and on enhanced lower trophic level productivity associated with enhanced nutrient supply.

7.4 Large Lakes

Although small with respect to tonnage, many locally important fisheries are located in lakes. This is particularly true in the less developed nations of Africa, South and Central American, and Asia. The Great Lakes system can serve as a model for lake fisheries as well as for the more complex marine environment. The lakes are large enough that spatial sampling problems are identical to those encountered in the oceans, yet in fact they do have definite boundaries and their present fisheries management practices reduce some of the uncertainties that commonly confound studies of open oceansystems. Lake Michigan fisheries, for example, are totally managed

at the top carnivore level, which gives scientists better control of the system under study.

From an experimental and modeling viewpoint, the Great Lakes may be particularly attractive for investigating the dynamics of fisheries because the fish have life cycles common to most lake species (e.g., large eggs, relatively low fecundity, deposit spawning). The low number of species and associated interactions as well as the limited number of physical and chemical factors that must be considered are advantageous for research on the lake system. The principal forage fish species, the alewife, is a marine fish that has successfully adapted to freshwater. Alewife populations have been highly variable, showing dramatic changes since the time of their introduction. Empirical data indicate that marked swings in alewife abundance may bestrongly influenced by harsh winters that severely limit recruitment.

8.0 Implementing a Fisheries Oceanography Research Strategy

Although recruitment research offers the promise of information that has great utility for fisheries and habitat management, it is a high-risk research topic. As such, there are no guarantees for success. The nature of the problem necessitates that a long-term financial and logistic commitment (5-10 years) be made. Recruitment studies have to extend for a number of generations of the species of interest. Efforts will focus on organisms with short life-spans and/or species for which there is an historical data base or some historical index of abundance (e.g., fish scales in sediments). Similarly, critical field experiments may have to await the occurrence of changes in the physical environment that are not predictable and occur at irregular intervals.

Currently most field research on fisheries recruitment conducted by NOAA elements particularly NMFS is "piggybacked" on existing survey and assessment programs. University research also is limited by the availability of vessel time and appropriate laboratory facilities. If significant progress is to be made, then the additional logistical support required will have to be provided. An effective fisheries recruitment program will make major demands on many NOAA agencies. The Environmental Research Laboratories must contribute essential expertise in meteorology and both physical and biological oceanography. The NOAA Undersea Research Program will be called upon to facilitate in the acquisition of special types of data and aid in the development and evaluation of sampling devices. The participation of the National Environmental Satellite, Data, and Information Service will be critical to track movements of large water masses, oceanographic and atmospheric frontal systems. To insure that appropriate locales are sampled at appropriate times, it will be necessary to coordinate scheduling of NOAA and UNOLS research vessels. Special emphasis must be placed on developing techniques for acquiring biological, physical, and chemical information during extreme weather conditions.

References

Anon. 1981. Oceanography from space. *Oceanus* 24(3), Fall 1981.

Bakun, A. 1983. Part III–Report of the working group on environmental studies and monitoring. In: G. D. Sharp and J. Sirke (eds.), Reports of the expert consultation to examine changes in abundance and species composition of nerific fish resources. San Jose, Costa Rica, April 1983. FAO Fish., Rep. 291(1):41-54.

Bakun, A. 1985. Comparative studies and the recruitment problems: searching for generalizations. CalCOFI Rep. 26:30-40.Boehlert, G.W. and M.M. Yoklavich 1986. Long-term cycles of growth in *Sebastes:* Extracting information from otoliths. Pro. Int. Rockfish Symp., Alaska Sea Grant.

Brewer, G.D., G.S. Kleppel, and M. Dempsey 1984. Apparent predation on ichthyoplankton by zooplankton and fishes in nearshore waters of Southern California. *Mar. Bio.* 80:17-28.

Carpenter, S.R. (ed) 1988. *Complex Interactions in Lake Communities.* Springer-Verlag, Berlin (in press).

Crecco, V.A. and T.F. Savoy 1985. Effects of biotic and abiotic factors on growth and relative survival of young American shad, *Alosa spaidissima,* in the Connecticut River. *Can. J. Fish. Aquat. Sci.* 42:1640-1648.

Dickey, T.D. 1988. Recent advances and future directions in multi- disciplinary in situ measurement systems. In: Toward a theory of biological-physical interactions in the world ocean, B.J. Rothschild (ed). Reidel, Dordrecht the Netherlands (in press).

Esias, W.E. 1981. Remote sensing in biological oceanography. *Oceanus* 24:32-38.

Fiedler, P.C., G.B. Smith and R.M. Laurs 1984. Fisheries applications of satellite data in the Eastern North Pacific. *Mar. Fish. Review* 46:1-13.

Francis, R.C., S.A. Adlerstein and A. Hollowed 1987. Pacific hake stock assessment: steady-state models applied to the assessment of a dynamic population. Paper presented at IRIS-INPFC Symposium on Recruitment and Errors in Stock Assessment Models. Vancouver, B.C., October 1987.

Hennemuth, R.C. 1979. Man as predator. In: *Contemporary Quantitative Ecology and Related Economics.*, pp. 507-532. Ed. by G.P. Pahl and M. Rosenzelg. Int. Coop. Publ. House, Fairland, MD.

Hollowed, A.B., K.M. Bailey and W.S. Wooster 1987. Patterns in recruitment of marine fishes in the northest Pacific Ocean. *Biol. Oceanog.* 5:99-131.

Kerfoot, W.C. and A. Sih (eds.) 1987. *Predation: Direct and Indirect Impacts on Aquatic Communities.* University Press of New England, Hanover, New Hampshire.

Koslow, J.A., K.R. Thompson and W. Silvert 1987. Recruitment to the northwest Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeylejinus*) stocks: influence of stock size and climate. *Can J. Fish. Aquat. Sci.* 44:26-39.

McConaugha, J.R. 1987. Blue crab larval distribution and recruitment. *Coastal Oceanography and Climatology News* 5(4):43-44.

Methot, R.D., Jr. 1983. Seasonal variation in survival of larval *Engraulis mordax* estimated from the age distribution of juveniles. U.S. National Marine Fisheries Service Fish. Bul. 81:741-750.

Mulligan, T.J. 1986. Stock identification based on elemental composition of otoliths. Int. Cors. Exp. Scos., C.M. 1986/M:19.

Ortner, P.B., R.E. Pieper and D.L. Mackas 1982. Advances in zoolplankton sampling. In: *Fish Ecology III*, B.J. Rothschild and C.G.H. Rooth (eds), pp. 355-379, University of Miami Tech. Rep. No. 82008, Miami, Florida.

Paine, R.T. 1980. Food webs, linkage interaction strength and community infrastructure. *J. Anim. Ecol.* 49:667-685.

Pietrafesa, L.J., G.S. Janowitz, J.M. Miller, E.B. Noble, S.W. Ross and S.P. Eppsily 1986. Abiotic factors influencing the spatial and temporal variability of juvenile fish in Pamlico Sound, North Carolina, p. 314-353, In: D.P. Wolfe, Ed., *Estuarine Variability*, Academic Press, NY, NY.

Rice, J.R., L.B. Crowder and M.E. Holey 1987. Exploring mechanisms regulating larval survival in Lake Michigan bloater: A recruitment analysis based on characteristics of individual larvae. *Trans. Amer. Fish Soc.* 116 (in press).

Shannon, L.V. (ed) 1985. South African ocean color and upwelling experiment. Sea Fisheries Research Institute. Capetown, South Africa.Sharp, G.D. 1987. Climate and fisheries: causes and effects in energy flows among coastal and offshore areas.

Smith, P.E. 1978. Biological effects of ocean variability: time and space scales of biological response. Rapp. P-V. Reun. Cors. Int. Explor. Mer. 173:117-127.

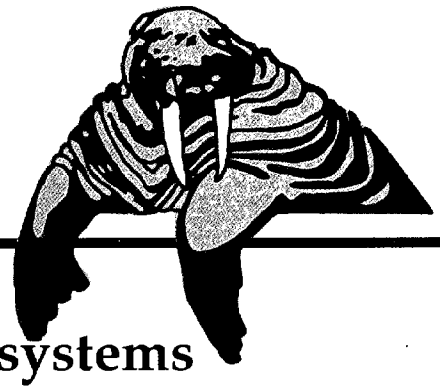
Steele, J., C. Clark, P. Larkin, R. Lasker, R. May, B. Rothschild, E. Ursin, J. Walsh, and W. Wooster 1980. *Fisheries Ecology: Some Constraints that Impede Our Understanding.* Ocean Science Board. National Academy of Science, Washington, D.C.

Ware, D.M. 1982. Power and the evolutionary fitness of teleosts. *Can. J. Fish Aquat. Sci.* 39:3-13.

Weller, R. and R.E. Davis 1980. A vector measuring current meter, *Deep-Sea Res.* 27:565-582.

Werner, E.E. and J.F. Gilliam 1984. The ontogenetic niche and species interactions in size-structured populations. *Ann. Rev. Ecol. Syst.* 15:393-425.

Wooster, W. (ed) 1983. From year to year: interannual variability of the environment and fisheries of the Gulf of Alaska and the Univ. of Washington, Seattle, 208 p.



Chapter IV

The Role of Sea Ice in Controlling Arctic Ecosystems

Executive Summary

Problem and Opportunity

Sea ice exerts an influential control over the Arctic marine ecosystem. Its extent, formation and melt are critical factors for the annual primary production cycle of the Bering Sea Shelf. Sea ice acts as a platform and habitat for mammals, and a substrate for the tiny plants that form the base of the food chain supporting birds, shellfish, fish and mammals. The ice meltwater stabilizes the sea and allows a strong spring pulse of food production, making the American Arctic one of the richest commercial fisheries in the world. The retreat of the ice edge through the Bering and Chukchi Seas is equal to fertilizing an area from Texas to the Canadian border and the Rocky Mountains to the Mississippi River. The Northern Bering Sea has recently been shown to have the world's highest primary production rates. Yet the critical pathways of energy flow from plankton to bottom organisms and then to commercial fisheries and mammals are not well understood.

NOAA, with its research capabilities, satellite imagery and environmental data archives, and fisheries mandates is well configured to address this important problem.

Understanding the role and dynamics of this process then will enable NOAA to provide resource managers the tools to perform closer management and to make more prudent fisheries allocation decisions. The lead time that this approach yields will also enable commercial fishermen, seafood processors, and the relevant markets to make smoother adjustments to resource variability and consequently to better allocate human and capital investments.

Research Strategy

The proposed research will test the hypothesis that interannual variation of maximum ice extent and seasonal ice retreat account for the major year-to-year variability in the biological productivity of the Bering and Chukchi Seas. Elements in this study include:

- *Re-evaluation of existing biological and physical data sets and initiation of an historical study using satellite and other remote sensing data,*
- *Biological and physical oceanographic sampling along the ice edge over an eight year period,*
- *Examination of the dynamics of primary production, nutrient recycling and fluxes at the ice edge,*
- *Examination of benthic population with respect to vertical flux of particulate material,*
- *Examination of the relation of ice edge primary production to occurrence and timing of zooplankton and larval fishes and crustaceans,*
- *Research on variability of high-latitude weather and its effect on ice extent, location, and timing,*
- *Study of sea ice and oceanographic processes in coastal areas by use of* in situ *and remote sensing techniques,*

- *Synthesis of field studies into models and examination of fish and mammal population dynamics in the light of the expanded data base on weather, sea ice and oceanography.*
- *Reactivation of the Bering Sea ice model developed earlier, its extension to the Chukchi Sea, and its use to design sampling strategies.*
- *Measurements of currents, nutrient dynamics, biological productivity and particulate flux in the vicinity of Bering Strait during the ice melt-back.*

Why Now?

Dramatic, largely unexplained changes are occurring in the Arctic system:

- *The king crab and Tanner crab harvests have plunged since 1979 with serious economic impact. Other commercial species such as pollock are being heavily exploited.*
- *The northern fur seal population is declining rapidly (4-8% per year). All large baleen whale populations have been severely reduced and may not be recovering. The walrus population has become very large and is in danger of crashing. Sea otter populations are increasing and competing with fishermen for shellfish.*
- *Dramatic increases in marine growth and survival have been documented for salmon populations of the Bering Sea. Recent indications of an end to the boom in production of the past ten years have very serious economic implications for both commercial and subsistence fisheries.*

Benefits

The ocean's productivity defines the limits on all marine biological systems. The work here will provide arctic marine ecosystem researchers with the basic input to estimate parameters of biomass, recruitment, exploitation, and competition. The answers to the important questions of production of groundfish, crabs, and salmon, and of the timing of salmon harvests, lie in understanding the dynamics of the Alaskan continental shelves.

In his statement on United States Arctic policy (April 14, 1983) the President emphasized that the United States has unique and critical interests in the Arctic region. In light of the region's strategic importance, the Administration feels that the Arctic warrants priority attention by this country. A review of national issues and priorities for the Arctic Research and Policy Act has been completed by the Polar Research Board of the National Research Council[1] and the U.S. Arctic Research Commission.[2] Based on these reports, both the Interagency Arctic Research Policy Committee (IARPC) and the State of Alaska established an implementation plan to address the structure of ecosystems of the major arctic shelves (Bering Sea, Beaufort Sea, Chukchi Sea) thorough integrated programs with a strong physical oceanographic and weather/climate component. They specifically identified the biological production and food web dependencies in relation to physical features such as ice edges, polynyas and hydrographic structures (i.e. fronts) as priority areas for research.[3] The Arctic and Antarctic are less well known than any other area of comparable size. Most Arctic-rim countries, particularly the Soviet Union, possess Arctic technologies far more advanced than those currently available in the United States. Sponsorship of currently neglected research in basic science is a necessary and proper function of the federal government to fulfill national objectives in Arctic research.

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[1] Polar Research Board. 1985. National Issues and Research Priorities in the Arctic. National Research Council, Washington, D.C. 123 pp.

[2] U.S. Arctic Research Commission. 1986: National Needs and Arctic Research: A Framework for Action. Los Angeles, CA. 27 pp.

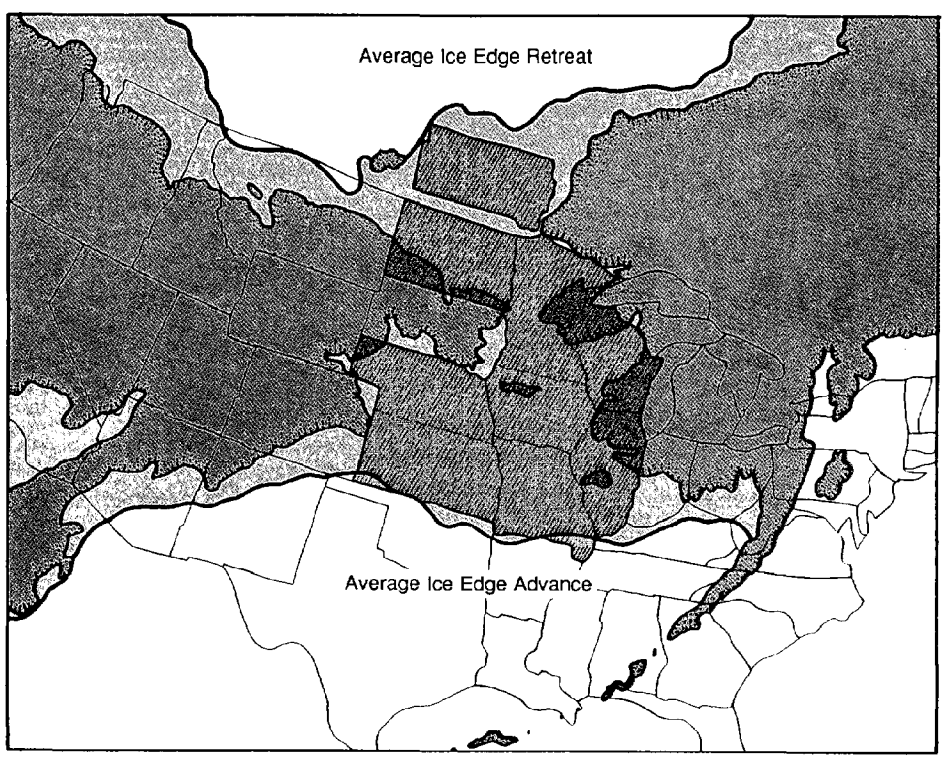
[3] Polar Research Board. 1985. Ibid, p. 44.

1.0 Introduction

The coastal aboriginal peoples of Arctic America developed cultures based on exploitation of the marine mammals and fish of the Bering, Chukchi and Beaufort Seas. The same resources were the basis for exploration and settlement of Russian America and later, the interests of distant water fishermen and whalers from the United States provided an important incentive for the purchase of Alaska. From the beginning the Arctic environment has been the major limiting factor in exploitation of these resources. Our knowledge of the role of ice in the ecosystem is critical for understanding and exploiting biological productivity. We now have some understanding of regional variations in primary production in the southeastern Bering Sea and ideas of the physical/chemical factors which produce these variations. The annual primary production cycle of most of the Bering Sea shelf is dominated by a spring pulse. Spring blooms occur at the onset of ocean stratification, with their duration highly dependent on storms to replenish the surface layer with nutrients. Nutrient enhancement by wind mixing from deeper layers is responsible for from 10% to 50% of the yearly spring bloom total nitrate uptake, depending on year. Ice cover plays an important role in determining the timing of the spring bloom. Increased stratification from ice melt allows the development of an intense phytoplankton bloom at the ice edge as soon as active meltback begins. Consequently, the growth season is initiated earlier than would be possible in the absence of sea ice. For this reason, variations in the southerly extent of sea ice in winter have major ecological consequences. The retreat of the ice edge fertilizes a region equivalent to Texas to the Canadian border and the Rocky Mountains to the Mississippi River of the continental U.S. (Figures 1 and 2).

The influence of year-to-year variations in sea ice extent and retreat is an important question if the impacts on the biological system are so extreme. A significant climatic change occurred during the span of the previous interdisciplinary Bering Sea ice edge work (1975, 1976, 1977, OCSEAP/NOAA; 1982, 1983, 1987, NSF/Ocean Sciences; 1983, 1985, 1987 ONR/Arctic Programs). The three years during the late 1970's were cold, whereas during the warm years 1982 and 1983 the ice only reached the latitude of St. Matthews Island. The warm period has extended through 1987. The decade of the 80's has been the

Figure 1 The biologically productive seasonal ice zone of the Bering and Chukchi Seas is roughly equivalent in area to the major grain producing regions of the American farm belt.

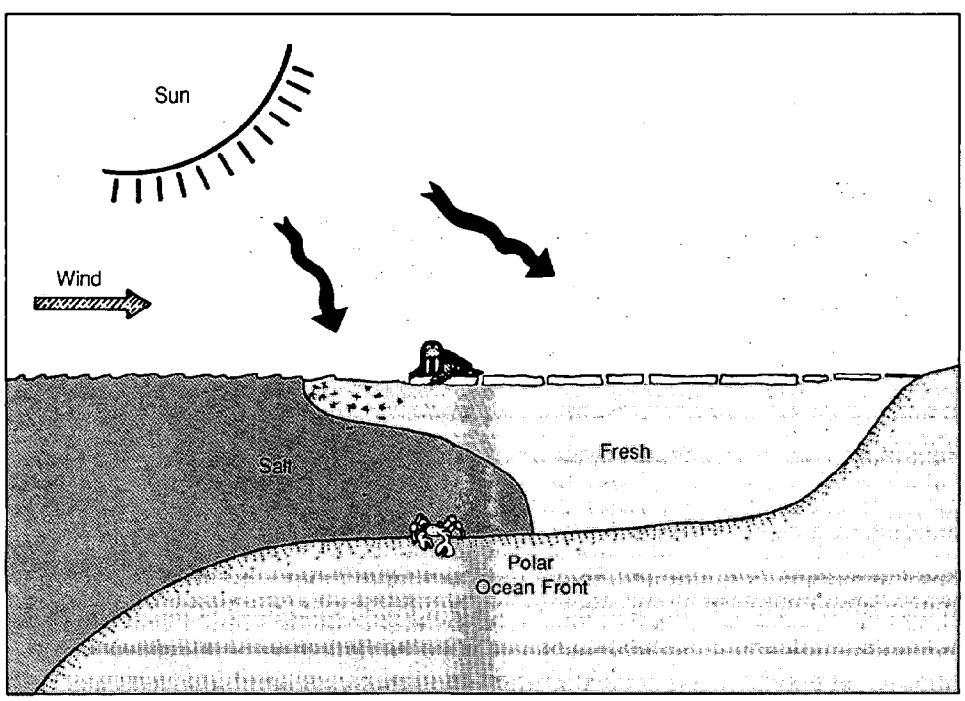


warmest decade measured to date. The first three years were cold with the ice reaching across the Bering Sea Shelf, whereas in the warm years 1982 and 1983 the ice only reached the latitude of St. Matthew Island. The chlorophyll content of the water at the ice edge and the primary production were significantly lower during the warm years than during the cold years. When the ice edge is closer to the shelf break, the higher nutrient concentration below the surface layer increases nutrient supply through ice-edge upwelling. Furthermore, the earlier water column stratification associated with ice melt prolongs the total bloom period. The total annual primary production in the outer shelf domain is probably increased significantly during a cold year. Therefore, we state the hypothesis for the ICE program as follows: Interannual variation of maximum ice extent and seasonal retreat account for the major year-to-year variability in the biological productivity in the Bering and Chukchi Seas. To clarify the effects of the position of the ice edge, it will be necessary to follow the ice northward during its retreat and examine variations in ice-edge phytoplankton productivity as the ice retreat passes over various parts of the shelf.

A large proportion of the ice edge production probably reaches the benthic community, since the grazing community in the water is small and not very active. As the bloom progresses, organic material sinks through the water column. Food chain relationships linking the ice edge and spring bloom to the other ecosystem components are not well known, but it seems reasonable that the rich benthos on the shelf and its top level consumers, shellfish, walrus, whales and fishes, are in part dependent on this efficient use of early-season solar radiation. In particular, the benthic-mammal food link maybe exceptionally important in the American Arctic, and these large organisms provide a degree of biological stability. Their role in nutrient recycling is not known. Spring bloom phytoplankton may also be particularly important in feeding juvenile fishes and crustaceans.

For crab, the period from egg hatch to settlement of larvae is likely to be the major determinant of year-class strength. The area of hatching must be more clearly delineated using intense survey efforts. Oceanographic and sea ice information is important in determining advection of larvae and subsequent settlement. Because considerable spawning and subsequent larval dispersion occur near the ice edge, ice edge phenomena may be important to this stage of crab larvae survival. This is particularly true for crabs in the northern Bering Sea and Norton Sound.

Figure 2 Melting sea ice stabilizes the water column at the ice edge promoting primary biological production as the ice retreats in the spring.



The seasonal variability of the extent of ice cover and of its residual melt water is governed by the storm climatology. Figure 3 shows the composite storm tracks for the 5 heaviest (A) and 5 lightest (B) years during 1958-1982. During the heaviest ice years the tracks were shifted southward along the Aleutian Islands and eastwards into the Gulf of Alaska. This gives rise to more north and northeast winds which move the ice farther south, increasing the extent of ice cover. During the lightest ice years (Fig. 3B) more storms move north across the western part of the Bering Sea. The result is a greater incidence of south and southwest winds on the shelf, compacting the ice cover and closing the ice-growing leads. Figure 3C shows the maximum extent of ice cover in the Southern Bering Sea. In an average year about one-half of the domain is covered. In heavy years ice surrounds the Pribilof Islands and covers the entire continental shelf. Interannual variability in seasonal sea-ice extent in the Bering Sea is controlled by variation in storm-track position related to large-scale differences in the general weather circulation.

2.0 Research Strategy/Goals

The research is based on a program of field measurements, historical analysis, and modeling. Physical process studies address the movement of ice by variable ocean currents, the relative importance of local radiation versus heat advection by currents to melt during ice retreat, and the link between seasonal and interannual atmospheric variability and ice extent. Biological process studies address the influence of the ice edge on primary productivity and the efficiency of transfer of energy from the surface to bottom living organisms. Remote sensing provides a means of longer term monitoring.

Modeling activities will synthesize the understanding of causal mechanisms between sea ice and the regional biology determined from the field studies with the historical atmospheric time series to test the ICE hypothesis and corollaries:

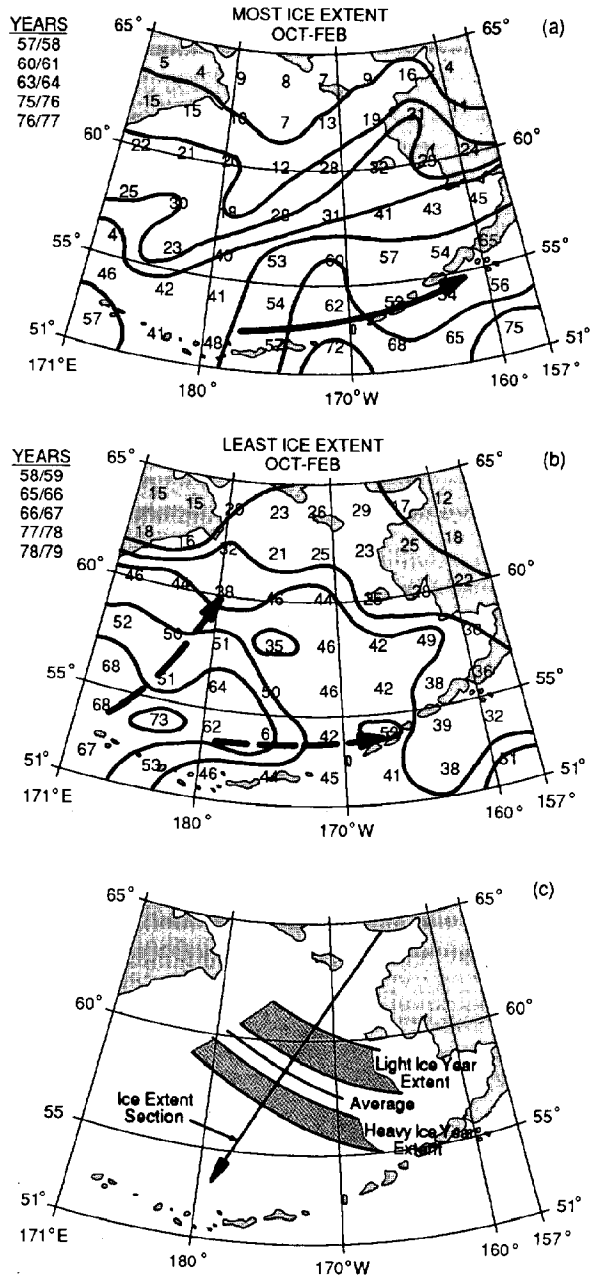


Figure 3 Storm track counts by 2° latitude v 4° longitude over October to February for the five heaviest (a) and five lightest (b) ice years in the period 1957 to 1980. The arrows suggest core pathways of the preponderant storms. Panel (c) shows the corresponding extents of the ice cover. (Overland and Pease, 1982: Monthly Weather Rev.)

2.1 Sea Ice Processes: Forcing by the Atmosphere and Ocean Determines Ice Conditions

To extend our knowledge of sea ice behavior and biological consequences to the northern Bering Sea, Bering Strait, Chukchi and nearshore Beaufort Seas, all regions of intense environmental, commercial, and strategic interest, three important physical processes must be considered. First, the transport of ice by ocean currents must be understood. Net ocean transport through Bering Strait is toward the north and over a year averages about 30 cm/s. On shorter timescales, meteorological forcing results in stronger events (current speeds up to 125 cm/s) which can reverse the flow over time periods of two to seven days. This current system varies remarkably in strength and direction and can cause the ice to move in the opposite direction as the local wind, but is poorly understood. Second, the role of heat advection by this current in the spring and summer months versus the local vertical heat flux and radiation balance in the melt-back of the ice pack is not known. Third, there is no realistic theory describing the interannual variations of ice cover and their relation to atmospheric circulation. Understanding of the seasonal cycle of arctic weather can be improved by basic research on the relation of high-latitude atmospheric circulation to forcing by the land and sea ice distribution and by lower latitude circulation.

The first measurement component of the ice program is an array of satellite-position drifting ice buoys deployed in key areas along the coast. These measurements will be used to evaluate the extent of shore effects from the coast on the ice velocity, to test open pack constitutive laws, and to create a nearshore constitutive law, if necessary. A second set of measurements will be conventional current meters and pressure gauges to address year-to-year and seasonal variations in ocean transport. A third measurement component will estimate thermodynamic variables. Sensible and latent heat fluxes from the atmosphere to the ice and sensible heat flux from the ocean to the ice can be computed by careful temperature measurements in the boundary layers. High resolution thermistors will be added to the anemometer and current meter masts at the drifting buoy sites for this purpose. In addition, a broad-band radiometer will be attached to each station for estimates of the solar and long-wave radiation incident on the upper surface of the ice. This measurement program will be able to differentiate the relative contribution to melting of the local radiation budget versus northward advection of heat by ocean currents. Studying the ice pack will require measurements over five years, since the interannual variability of the weather conditions and the severity of the resulting ice conditions is large. The variability of the barotropic current component through the Bering Strait also has large variations from year-to-year which may affect the ice drift patterns.

The coupling between the atmosphere and sea ice on seasonal and interannual time scales will be addressed by detailed analysis of the North Pacific Oscillation (NPO) from historical atmospheric data sets in the context of the northern hemispheric general circulation. The first element is to determine the persistence of the NPO as a basis for statistical prediction. Such approaches have not been entirely successful at mid-latitudes, but, since the duration of NPO events is often greater than 10 days and the anomalies are large, such approaches should be attempted. Statistical methods now exist but they must be based upon more complete causal hypotheses. The data base which exists for the study are the sea level pressure, 500-1000 mb thickness (which correlate with air temperature) and 500-mb steering level wind fields beginning in 1947 as well as long time series of weather observations from Arctic stations and sea ice extent fields derived from satellite observations continuously since 1969 and sporadic before that time.

A second feature is to systematically assess the possibility of positive feedback of heat between atmosphere, land, and ice surfaces for the sub-Arctic. It is known that the land/sea distribution and coastal orography provide forcing to the long-wave atmospheric circulation pattern. Of particular concern to the seasonal time scale is the feedback between the seesaw relation of Bering Sea and the Sea of Okhotsk, and the Alaska and Siberian landmasses. The thermal mass of Alaska and Siberia are substantial and ground temperatures can increase by several ten's of degrees over a week's time. These temperatures reinforce the long wave atmospheric weather patterns ability to maintain the existing storm track pattern. Sea ice acts as an extension of the continent and effectively acts as an insulator between the air and the relatively warm sea temperatures. When ice is retreating in the Bering Sea due to southerly winds, it is advancing in the Sea of Okhotsk. It is not known whether this relative ice motion tends to reinforce the existing weather pattern.

2.2 Biological Processes: The solar-induced spring bloom at the ice edge generates a pulse of food for the benthos.

The renewable resources of the American Arctic, specifically fish and shellfish, represent one of the Nation's greatest commercial assets. Yet there are dramatic, unexplained fluctuations in the resources. The recent catches of king crab in the Bering Sea are shown in Figure 4. This was an international fishery shared with Japan and the USSR until the United States developed the capacity to capture the full harvest in 1981. The catch grew rapidly from 1958 until 1963, reaching a peak of 28,000 mt, then declined from 1964 until 1971 to a low of 9,000 mt. It rapidly increased from 1972 until 1979 with a peak harvest of 65,000 mt, and has since declined to less than 5,000 mt in 1985. Such large year to year variability in stocks, both natural and that due to fishing, has created major difficulties for both industry and management.

The Bering Sea is a vitally important rearing and feeding ground for a majority of the salmon stocks which serve as cornerstones for a large number of commercial and subsistence activities in Alaska and other areas of the Pacific Rim. Very dramatic recent increases in commercial production (Figure 5) from 21.9 million salmon in 1974 to 144.6 million in 1985

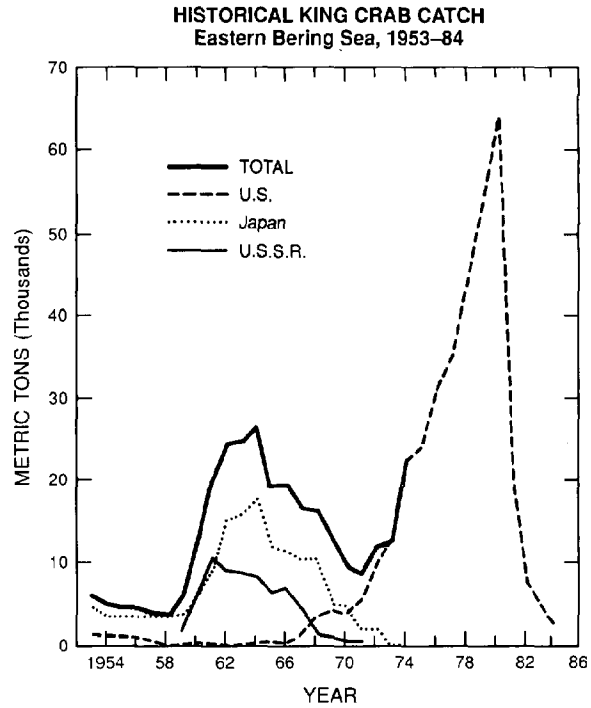
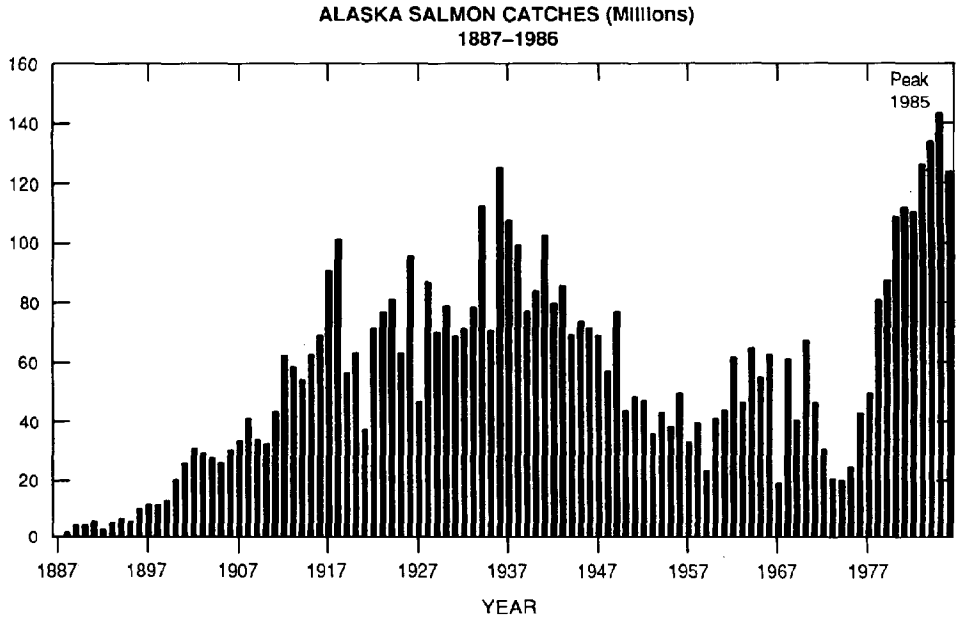


Figure 4 Recent catches of king crab in the Bering Sea.

Figure 5 Recent explosive increase in commercial salmon production from 1974 to 1985.



have illustrated the importance of the marine environment in determining the well-being of both subsistence and commercial fisheries.

The biological sampling strategy is to make standard nutrient dynamics, productivity and vertical flux measurements in the vicinity of the melt-water stabilized region of the ice edge and contrast these measurements with adjacent open-ocean measurements. These tasks will follow the retreat of the ice edge through the Bering and Chukchi Seas. The second part of the sampling strategy is to determine benthic (bottom) biological activity to determine the efficiency of transfer of energy from primary production to bottom fauna. The shallow Bering and Chukchi Seas may be unique in their efficiency of transferring energy from the ice edge enhanced primary productivity to higher trophic level species via intermediate bottom communities. Sampling will be oriented on primarily south-north transects and will occur during spring ice retreat. Measurements will be required over a five year period to provide representative sampling and consider year-to-year variability. This strategy will allow determination of the variations in the importance of ice by biological regimes over the entire north-south area. To date, ice edge biological work has been restricted to its southwest parts.

In parallel with field experiments, efforts to model regional ice/ocean circulation, heat budget, and biological system will be undertaken. Initially modeling will concentrate on regional ocean circulation, ice drift, and stabilization of the mixed layer by ice melt. As results from the field measurement programs and atmospheric studies become available, systems studies can be formulated to address the causal links between interannual atmospheric variability and year-to-year changes in the biological communities of the Bering and Chukchi Seas.

These measurements will be used by the Alaska Department of Fish and Game to test the hypothesis that the times of arrival of maturing salmon at the fixed geographic reference frames sampled by commercial fisheries are driven by physical factors related to ice edge location.

2.3 Remote Sensing Support: To economically monitor the ongoing ice/biological interactions.

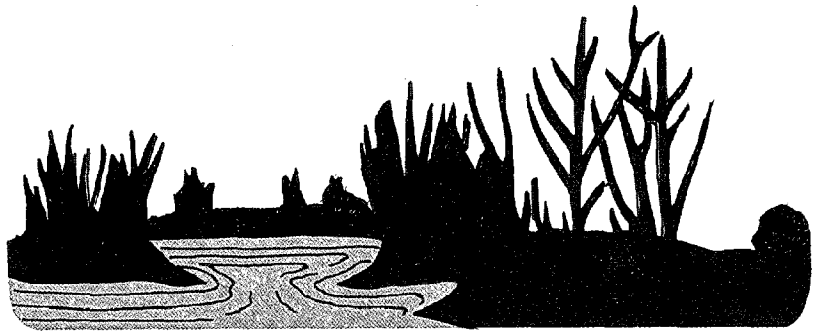
In situ measurements of sea ice and biological processes are cumbersome, expensive, and limited with respect to aerial coverage and spatial and temporal resolution. Fortunately, the presence or absence of ice on the ocean affects virtually all regions of the electromagnetic spectrum and is, therefore, an ideal parameter to be measured remotely from space.

The first promising instrument is the passive microwave imager, SSM/I, flown on the DMSP satellite in 1987. The bands selected for passive microwave sensing are largely unaffected by clouds and require few atmospheric corrections at high latitudes. At present a single reading is incapable of being interpreted beyond the statement that ice is present or absent. With the new instrument, it should be possible to use a set of multi-spectral, multi-polarization readings to distinguish various sea ice properties for Alaskan waters.

The most powerful instrument, combining high spatial resolution with virtual independence of atmospheric effects, especially in the dry polar atmosphere, is the synthetic aperture radar (SAR). The European Space Agency plans to launch a satellite (ERS-1) with SAR in 1990. A SAR receiving station for ERS-1 is planned for Fairbanks, Alaska which will be made available for dissemination SAR data for research, and will provide the all-season, all-weather data base necessary for sea ice processes research on scales as small as 25 m. Analysis of SAR imagery will provide baseline information for verification of the sea ice and climatology models proposed for the Alaska region. Biological studies can benefit from synoptic coverage with color imaging for chlorophyll, a measure of phytoplankton biomass. Aircraft-based capability would be of greatest use, to provide coverage in communities with less surface-based sampling from a research vessel.

3.0 Summary

The hypothesis to be tested by the ICE program is that the interannual variability of the location of maximum ice extent and seasonal ice retreat is the primary cause of year-to-year variation in the biological productivity of the waters of the American Arctic. This program will implement the highest priority research recommendation of the U.S. Arctic Research Commission as mandated by the Arctic Research and Policy Act of 1984. The program is based on a ten-year program of physical and biological field measurements, study of historical variability of arctic weather and its influence on ice motion, and modeling. Modeling activities will synthesize the understanding of causal mechanisms between sea ice and the regional biology determined from the field studies with the historical atmospheric time series to test the ICE hypothesis.



Chapter V

Estuarine Systems: Productivity and Environmental Change

Executive Summary

Problem and Opportunity

Estuaries and their associated coastal waters are a valuable and yet vulnerable component of the marine environment. They provide the biological foundation for our productive coastal waters. In the United States, two-thirds of the commercial fisheries harvest is estuarine-dependent. Future economic and population growth is forecasted for our coastal and estuarine areas, such that by 1990, 75% of the U.S. population is projected to live within 50 miles of the coast. Our estuaries are already suffering the consequences of accelerated heavy use. Evidence shows that the health of our Nation's estuaries is declining. Degradation of environmental quality and subsequent economic costs in the form of fisheries losses and threats to public health and safety have become widespread. Low oxygen levels in bay waters have resulted in massive fish kills. High levels of toxic contaminants have been reported in sediments and benthic organisms from urban estuaries. There is widespread disappearance of submerged aquatic vegetation; there is continued loss of coastal wetlands; and there are dramatic declines in estuarine-dependent species including oysters, clams, striped bass, and shad.

Recognizing the urgent need for action to maintain and enhance the ecological integrity of the Nation's estuaries, the U.S. Congress has urged the development of management plans for these critical areas. OAR research can provide an insight into the functioning of these systems. Such information is essential for developing a capability to predict responses of estuarine environments to human actions and natural events, and for implementing cost effective strategies to manage these systems.

Research Strategy

Until understanding of estuarine processes and the effects of human activities on these systems increases substantially, costly uncertainty will remain regarding the effectiveness of alternative management strategies. OAR will implement a scientific program focused on estuarine productivity in five target estuarine habitats: Spartina *marshes, seagrass beds, mangrove forests, unvegetated flats and the water column. Unlike many previous estuarine research programs, which emphasized studies of whole estuaries or specific pollutants, this approach will examine and compare the factors controlling productivity in a limited number of estuarine habitat types across the country. Research will focus on four themes:*

1. *The effect of variation in freshwater inflow on physical structure and biological productivity in estuarine habitats.*
2. *The effect of nutrients and nutrient cycling on habitat productivity.*
3. *The relationship of habitat structure to habitat productivity, including the cumulative effects of habitat loss on productivity.*

4. *The relationship between the nature and functioning of estuarine food webs and habitat productivity.*

Why Now?

Recent legislation (e.g., the Clean Water Act and the Water Quality Act of 1987) and actions by Federal administrators have placed estuaries in the limelight. Legislators, environmental managers, the media and the general public are being made increasingly aware of estuarine systems, their importance to coastal environments, and the potential harm that may come to these systems as a result of short-sighted or inadequate management. This heightened awareness coincides with the maturation of many subdisciplines within environmental science. In particular:

- *Improved computer technology and techniques, and enhanced modeling capabilities enable, for the first time, description of estuarine dynamics with some realism.*
- *New instruments and facilities, and a better understanding of the time frames of estuarine processes can now be applied by scientists to achieve major new insight into estuarine processes.*

NOAA has in place a core program of estuarine efforts and is positioned to undertake a focused, comprehensive study of estuaries. Additional research funds for NOAA, its researchers and their academic colleagues will permit the agency to build upon these strengths.

Expenditures of funds on site-specific problems are seen as a poor investment for developing a national approach to estuarine management by a research rather than a resource management agency. Needed now are studies on the basic functioning of estuarine habitats and relationships to overall productivity around the country.

NOAA is poised to initiate multidisciplinary and multi-institutional research to address critical estuarine issues. Failure to exploit this opportunity will result in a loss of research momentum, and could deprive society of information needed to wisely manage estuaries into the 21st century.

Why NOAA?

The Federal government has a role in estuarine governance, especially where estuaries and uses of their resources cross geopolitical boundaries. As the Nation's lead civilian ocean science agency, NOAA is uniquely qualified to assist in this role by conducting a program to increase understanding of estuarine systems, and by providing information necessary to predict and assess changes in these systems. NOAA's diverse capabilities in atmospheric science, ocean systems dynamics, biological processes, resource protection, and coastal zone management provide a pool of expertise capable of addressing major estuarine problems in a comprehensive manner.

- *NOAA has a national network of estuarine/coastal facilities that includes 27 NOAA laboratories, 17 Estuarine Research Reserves, Sea Grant Programs, and several NOAA/academic cooperative institutes.*
- *NOAA employs or funds many of the Nation's outstanding estuarine scientists, some of whom serve in NOAA's research laboratories and others who are associated with NOAA through existing programs.*
- *NOAA scientists have excellent relationships with scientists in academia. These relationships have formed the bases for partnerships among estuarine interests in NOAA, the academic community, and the states. These partnerships can be used to provide expertise to respond to research and assessment needs.*
- *The partnerships between NOAA and academia can be used efficiently and effectively through the National Sea Grant College Program to respond to complementary needs for long-term estuarine research and monitoring as well as for short-term process-oriented studies.*
- *NOAA is sensitive to resource management needs. In partnership with the states, NOAA is responsible for managing living marine resources and the coastal zone. Additionally, NOAA advises other agencies (e.g., U.S. Army Corps of Engineers and Environmental Protection Agency) on living marine resources, under numerous legislative directives.*
- *NOAA has a great deal of experience in predicting and forecasting–experience that should be directed to estuaries.*

NOAA's role and experience in environmental prediction and forecasting will form the basis for tying these resources and responsibilities together.

Benefits

Scientific findings from this program will improve our understanding of estuarine productivity and thereby provide the critical knowledge needed to:

- *Develop appropriate water management strategies,*
- *Develop cost-effective pollution control strategies,*
- *Maintain and restore critical estuarine habitats,*
- *Restore and enhance estuarine-dependent fisheries,*
- *Improve our ability to sustain and increase long-term economic returns from estuaries through recreation, resource extraction, transportation and waste disposal.*

This new knowledge can be used by resource management agencies to develop cost-effective regulations, improve permitting, and reduce litigation. The ultimate benefit will be enhanced economic development through the wise use and managment of estuaries.

1.0 Background

Estuaries and their associated waters are a valuable, yet vulnerable component of the world's oceans. Although the estuarine/coastal complex comprises less than one percent of the marine environment, it is by far the most productive. *Spartina* salt marshes, for example, produce ten tons of organic material per acre per year, compared to four tons per acre per year produced by fertile hay fields. Estuaries provide the food, shelter, and spawning grounds for over 70 percent of the Nation's commercial fisheries landings by weight and over 66 percent of these fisheries by value ($5.5 billion in contribution to the GNP in 1986). Seven of the ten most valuable commercial fisheries–Gulf shrimp, sockeye salmon, menhaden, pink salmon, oyster, South Atlantic shrimp, and blue crab–depend on estuaries to survive. The estuarine/coastal system is equally critical to sustaining recreational fishing: an estimated 17 million sport fishermen in the Nation generate expenditures of over $7.5 billion annually.

Estuaries also are important to society as avenues for transportation, sites for industrial development, areas for the disposal or treatment of wastes, and environments for recreation. These and other conflicting uses may be taking their toll on estuarine ecosystems. Several trends suggest there is cause for concern over the well being of estuaries:

- the demographic shift toward the coastal zone is placing increased demand on estuaries for transportation, waste disposal, urban development, recreation, and natural resources;
- nationally, the loss of estuarine wetlands has increased from about 20,000 acres per year to more than 30,000 acres per year, over the last ten years;
- *hypoxia*[1]-related fish kills have increased in frequency and severity, as has the incidence of disease in estuarine finfishes and shellfish; and
- landings of many economically-important estuarine-dependent fishery stocks show long-term declines.

Although excellent research on estuaries is being conducted:

- ongoing estuarine research often is short-term, reactive and oriented toward local problems; and
- basic research often is fragmented and accomplished on small scales.

There is need for a national program of fundamental research on estuaries that will lead to a quantitative understanding of these systems, and ultimately to the ability to predict the implications of changes to estuarine environments. To be fully successful, such a program must include provisions for interpreting findings as they become available and in terms that are relevant to managers. An integrated program of fundamental estuarine research is required if estuarine resources are to be managed wisely.

2.0 Conceptual Approach

Research undertaken as part of the estuarine research program will focus on *estuarine productivity*[2] and factors that control secondary productivity within specific *estuarine habitats*. The ultimate goal of work

[1] *Hypoxia* refers to a level of oxygen dissolved in water that is stressful to organisms; generally, the level is defined as less than 2 milliliters oxygen/liter water.

[2] *Estuarine productivity* can be considered in two principal forms: primary productivity and secondary productivity. *Primary productivity* refers to the creation of organic compounds (fixation of carbon into organic forms) by plants, while *secondary productivity* is the growth of animals that consume plant materials, either directly or indirectly.

is to develop the capability to *predict* estuarine productivity (quality and quantity) in the face of environmental change.

The research program will focus initially on comparing productivity in a limited number of target estuarine habitats. Investigation of estuarine productivity, focused on target habitats, offers an alternative to previous studies that have attempted comprehensive examinations of single estuaries, or investigations that have focused on specific estuarine wastes or pollutants. The comparative approach will improve generic understanding of estuarine processes.

The more tightly focused comparative habitat approach will make estuarine studies more tractable and allow comparisons of estuarine productivity in similar *and* in different habitats over space and time. Specifically, the approach:

- overcomes problems associated with the complexity and heterogeneity of large estuarine systems, by limiting the number and types of habitats and species to be evaluated;
- reduces overall effort needed by focus on similarities among estuaries instead of uniqueness of individual embayments; and
- enables application of process-oriented findings within similar habitat types around the country.

Given the program focus, there is a high probability that efforts will result in substantive "breakthroughs" in understanding of estuarine productivity and, thereby, will provide critical information necessary for effective estuarine management nationwide.

The United States Fish and Wildlife Service (F&WS) has developed a classification system of wetlands and deepwater habitats. This F&WS system was designed by wetlands scientists, with input from resource users of the private and public sectors. The classification system provides a flexible framework for delineating habitats, based on interactions of both physical and community structure criteria–including salinity regimes, flooding periodicity, substrate type, vegetative life form, and species dominance type. From this classification system, five target habitats have been selected for study: *Spartina* marshes, seagrass beds, mangrove forests, unvegetated flats, and water column systems. These habitat types were selected on the basis of pragmatic criteria, including:

- aerial extent in the Nation's coastal zone;
- present and projected rates of loss and degradation;
- contributions to living marine resources, through both primary and secondary productivity.
- amenability to a range of experimental designs and scales; and
- appropriate scales for management activities.

The *Spartina* marsh and seagrass bed habitats will be the initial foci of the program. Once the program is well underway, other habitats will be considered for study. Following are general description of each of thefive habitat types selected.

2.1 *Spartina* Marshes

Spartina is the dominant plant type of coastal salt marshes of the United States. On the East and Gulf Coasts, *Spartina* dominates the extensive coastal marsh areas that extend from Maine to Georgia, and along portions of the Gulf of Mexico. On the West Coast, *Spartina* marshes occur in the Southern California and San Francisco Bay areas. Salt marshes are believed to serve as nurseries for juvenile fishes and invertebrates, contribute shelter and nutrition for an array of fishes that migrate with the tides, act as coastal stabilizers from storms, and play a role in land accretion through the trapping of sediments and the formation of peat from decomposed marsh plants. In effect, such sediment trapping and peat formation will, in the very long term, cause these habitats to filled completely, thereby bringing about their natural demise.

Spartina species exhibit high rates of primary productivity and contribute to secondary productivity primarily through the detrital foodweb[3]. Historically, *Spartina* marshes have been dredged for navigation and cleared, drained and filled for development. The potential long-term losses associated with destruction of this habitat include reduction of fisheries productivity, destabilization of shoreline areas, and reduction of overall productivity of these and adjacent habitats.

2.2 Seagrasses

Seagrass beds constitute one of the world's most conspicuous and common coastal habitat types, and contribute a large portion of the total primary productivity of estuarine ecosystems. These plants are dominant in many areas of the Pacific Northwest, the Bering Sea, the entire coastline from North Carolina to Texas (except South Carolina and Georgia), and Puerto Rico, the U.S. Virgin Islands, and Hawaii.

[3]*Food webs* refer to the matrix of plants and animals through which energy and materials flow.

Rhizomes and upright leaves of seagrasses allow the trapping and holding of sediments in coastal bays, thereby increasing protection from storm abrasion.

Seagrasses form the basis for an abundant and diverse assemblage of plants and animals. They exhibit high rates of primary productivity, producing large amounts of organic matter. This organic matter serves as food for grazing animals such as fishes, birds, turtles, and manatees, and, as detritus, supports a complex community that includes bacteria, benthic algae and encrusting invertebrates. Little is known about the natural variability of the functional relationships of seagrasses or about the trophic linkages within and between these and adjacent habitats. Recent quantification of seagrass habitat losses suggests a linkage with reduced fish productivity and general degradation of estuarine quality.

2.3 Mangroves

Mangrove forests dominate 75 percent of the world's tropical and subtropical coastline, developing in low-lying areas where fresh water is supplied to the coast by rivers or terrestrial run-off. Four species occur in Texas, Louisiana, Florida, Puerto Rico, U.S. Virgin Islands, and Hawaii. Mangroves have thickly entangled aerial prop roots that contribute to shoreline stability by reducing tidal influences and dissipating wave energy. While mangrove habitats produce large amounts of organic matter, their major contributions to the functioning of estuarine systems include: the deposition of nutrient-laden mud and silt; the provision of sites for attachment, breeding and nursery areas; and shelter for crustaceans/mollusks and vertebrates. The decomposition of leaves maintains a detrital food web believed to support an extremely diverse community.

Realization of the ecological value of mangrove assemblages is only recent. On a global scale, mangrove habitats are being cleared at alarming rates to provide charcoal and timber, and to create space for aquaculture ponds, marinas, housing, and industrial development. While mangroves form only a small part of the estuaries of the United States, they are important ecologically where they occur. Once destroyed, they recover slowly.

2.4 Unvegetated Flats

Unvegetated flats are those portions of the bottom of sounds, lagoons, estuaries, and river mouths that lie between high and low water and lack macroscopic plants. These flats are common in many estuarine areas of the U.S. Virgin Islands, and Hawaii. Unvegetated flats frequently occur adjacent to habitat types including mangroves, seagrasses, and *Spartina* marshes. While an intertidal flat appears barren of flora, a host of organisms may be found, including micro- and macroalgae, and benthic invertebrates (such as oysters, clams, mussels, and fiddler crabs) that utilize this habitat as feeding grounds during periods of high tide. Unvegetated flats are an integral part of the estuarine regime, providing food and substrate, especially for burrowing organisms.

2.5 Water Column

Estuarine waters exhibit regions of strong horizontal and vertical density gradients. These regions generally form at the boundaries between water masses of differing temperature and/or salinity. Horizontal regions of rapid density change are called frontal zones. These may occur both within an estuary and as plumes extending from the mouth of an estuary. Vertical regions of rapid density change are termed pycnoclines. In temperate waters, pycnoclines generally form in spring/summer when the density of surface water is reduced as the result of freshwater runoff and seasonal warming. This buoyant plume overrides colder, more saline water at depth.

Conditions within estuarine water column habitats reflect dynamic processes occurring within and between the strata, between the water and the overlying atmosphere, and between the water and bottom sediments. Pycnoclines and frontal zones are of special interest because they concentrate particulate materials such as suspended sediments and associated contaminants, bacteria, phytoplankton and zooplankton. Unlike the previous four habitat types discussed, the nature of the water column habitat is variable over relatively short time scales (e.g., minutes to hours), as well as over more commonly examined diurnal/tidal, seasonal and annual regimes. Variations are determined by the physics of estuarine processes. The functioning of water column habitats is of special interest in estuaries that suffer from nutrient over-enrichment.

3.0 Program Hypotheses

In order to improve abilities to describe and predict changes in estuarine productivity that result from natural factors and human-related activities, it is necessary to improve substantially our understanding of estuarine ecosystem functioning. This can be accomplished by testing the following central hypothesis:

> Central Hypotheses: Changes in estuarine productivity are functions of human-induced and natural alterations upon habitat structure and food web dynamics.

Figure 1 provides a general indication of the relationships between habitat substructure[4] and function, food web structure and function, and their influences upon estuarine productivity. For research purposes, the central hypothesis has been case into four supporting hypotheses that deal with specific ecosystem functions or structural components. These four provide focus for specific research thrusts that are critical in quantifying estuarine productivity and man's impact on it. Figure 1 shows conceptual linkages among these research thrusts. Important research questions and strategies that help quantify the linkages and provide understanding for the supporting hypotheses have been identified. Addressing the supporting hypotheses by specific habitat type will provide major new insight into human-related changes that impact estuarine productivity. Problem areas and proposed research strategies for addressing the supporting hypotheses are described in the text that follows.

A major problem area not addressed in this program is contaminants. Both NOAA and EPA have already established sizable research programs on contaminants. The result of this estuarine research program will be integrated with the results of the existing contaminant programs through synthesis efforts.

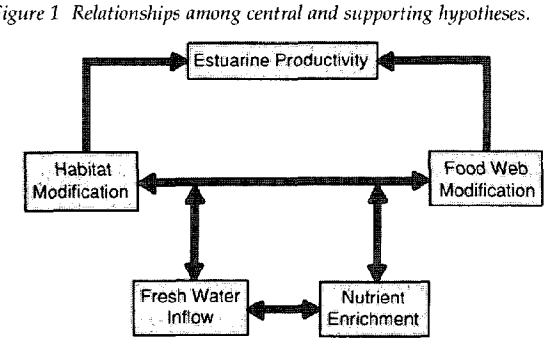
[4]It is important to note that habitat type and habitat structure are quite different. *Habitat type* is a generic term that refers to the dominant component or ecological unit of an area. For example, *Spartina* marsh is a recognizable habitat type because it is dominated by a single plant species. Other major habitat types include seagrass meadows, mangroves, intertidal flats, etc. *Habitat structure*, however, refers to the biological, chemical and physical components that comprise a habitat type, and that contribute to and regulate the primary and secondary productivity of the habitat.

> Supporting hypotheses: Changes in the volume and/or timing of freshwater and sea water inflows into estuaries alter the physical structure and biological processes within estuarine habitats.

Estuarine circulation and inflows of freshwater and sea water exert major influences on estuarine habitats. Data indicate that changes in the volume and/or timing of freshwater and sea water flows into estuaries affect biological processes and biological productivity. Modifications of the timing and flux of freshwater and sea water into estuaries are known to affect the structure, location and intensity of density fronts. Climatic changes (e.g., seasonal, interannual, decadal) modify the extent and timing of annual freshets. Environmental warming could contribute to prolonged density stratification and increased occurrences of hypoxia. Episodic events, such as storms, can create physical changes in estuarine morphology that otherwise would take decades or more to occur.

Redistribution and allocation of freshwater resources are major problems facing the Nation's estuaries. Changes in land use patterns, such as removal of ground cover around estuaries and along upstream tributaries inevitably affect the quantity, quality, and timing of freshwater inflows. Similarly, removal of freshwater from riverine systems, for irrigation and municipal water supplies, alters salinity distributions and dilution capabilities of estuaries. Human-induced modifications of inlets and channels also may alter the movement of sea water into estuarine areas. Attendant with such changes are variations in frontal structure that can affect transport of suspended sediments, nutrients and contaminants in the water column. Recruitment of many fish and shellfish stocks is closely linked to hydrodynamics of estuaries and associated coastal waters, as are the composition and well being of estuarine plant communities. Water

Figure 1 Relationships among central and supporting hypotheses.



management, thus, is integral to effective estuarine management. Among the important questions that require resolution with regard to this supporting hypothesis are:

- How do changes in freshwater and saltwater inflows affect productivity of estuarine habitats?
- What are the effects of alterations in freshwater and saltwater inflows on the structure of the water column, sediment distribution, and dissolved and particulate loads of nutrients and carbon?
- What is the relative importance of episodic events, such as storms and floods, in controlling estuarine productivity?

Supporting hypothesis: Human-related nutrient loadings to estuarine waters adversely affect estuarine habitat productivity.

Nutrient additions are increasing in many estuaries because of increased use of inorganic fertilizers and the conversion of wetlands to urban and agricultural uses. Unfortunately, at present, there is insufficient understanding of the multiple relationships between nutrient inputs, nutrient recycling, and ecosystem productivity to aid substantially in the management of estuaries. Associated problems that have been identified include shifts in the productivity, composition and abundance of phytoplankton, and reductions in the abundance and extent of desirable rooted aquatic plants. Such changes often are associated with reduced dissolved oxygen and reduced light penetration (which further affects the stability of estuarine habitats).

These ecological changes can be detrimental to the production of estuarine-dependent organisms through shifts in food resources and changes in the availability of suitable habitat. At present, it is not possible to predict in a quantitative fashion the consequences of such changes to estuarine productivity. The following are among issues to be addressed with regard to nutrient loading, productivity, and trophic structure:

- What is the relative importance of external nutrient sources and internal nutrient cycling?
- How do primary and secondary productivity vary as functions of nutrient level?
- What changes in community composition occur in conjunction with increased levels of nutrients?

Supporting hypotheses: Natural and human-related perturbations alter the transfer of energy and lead to changes in the secondary productivity of estuarine habitats.

High levels of estuarine finfish and shellfish (secondary) productivity appear to be associated with high levels of estuarine plant (primary) productivity. The latter may be as much as two to five times that of lakes, streams and waters of the continental shelf. However, the relationship between primary and secondary productivity is not understood well enough to develop informed management decisions concerning fishery and habitat management. Recent declines in a number of economically important fisheries have been attributed to overfishing, loss or modification of nursery habitat, or natural cycles. Unfortunately, there is little information to indicate how environmental management decisions have altered food webs and, thus, have impacted productivity in desired species. Previous research has been largely qualitative or descriptive. Emphasis must now be placed on understanding the dynamics of trophic interactions. Improved understanding of pathways that lead to secondary productivity is needed. With this information, resource managers will be better able to oversee estuarine-dependent living marine resources that might otherwise be threatened by overfishing and/or habitat degradation.

The following are among the issues to be addressed with regard to estuarine trophic dynamics:

- What are the food web linkages between plant productivity and the productivity of living marine resources within estuarine habitats?
- What factors determine the relative importance of food web linkages? What are the implications of shifts among the pathways to secondary productivity?
- How are primary and secondary productivity in estuarine habitats partitioned among loss to human harvest, loss to neighboring habitats (estuarine and coastal), or retention and cycling within the habitat?

Supporting hypothesis: Habitat modification disrupts the physical structure of estuarine environments, leading to reduced capacity for biological productivity.

A variety of estuarine habitats is required for spawning, growth, and survival of estuarine-dependent organisms. The productivity or yield of many species of living marine resources has declined during the past 25 years, coincident with deterioration and physical loss of estuarine habitats–due primarily to human activities. Correlations of habitat deterioration and declines in productivity can be drawn, but there is a lack of well documented cause and effect relationships between habitat deterioration and loss with loss in productivity of living marine resources. The most critical limiting habitat factors that affect fisheries productivity include: acreage and configuration of habitat type; predator-prey relationships; and habitat use by resource species at different life stages. To date, studies have established what habitat types appear important to living marine resources, but the specifics of how these habitats are used or which aspects of habitats make them valuable for growth and production of living marine resources are poorly known. Without this information, it is not possible to predict quantitative cumulative effects of habitat modification on productivity of living marine resources. In addition, lack of fundamental knowledge of the value of different habitat types to resource productivity also precludes realistic assessment of remedial mitigative action. The latter must be judged not only in terms of replacement of physical habitat, but in terms of replacement of functions and processes (e.g., utilization by fishes and shellfish) similar to those in unperturbed habitats.

The following are examples of issues to be addressed with regard to estuarine habitats:

- What are the relative values of estuarine habitats to the productivity of living marine resources?
- What are the cumulative effects of habitat loss and alteration on populations of living marine resources?
- Are mitigation and enhancement methods viable approaches to ameliorating habitat loss? Does habitat produced as a result of mitigation serve the same functions as the undisturbed habitat?

[5]*Ecological models* may vary from relatively simple verbal or mathematical descriptions of the functioning of estuarine habitat types to quantitative formulations. Models will form the basis for interpreting and predicting the response of estuarine habitattypes to human-induced and natural environmental alterations.

[6]Mesocosms are artificial environments, often in the form of large aquaria, in which estuarine habitat types may be simulated. Plants and animals are included, insofar as possible. Mesocosm studies enable scientists to vary one or more factors (e.g., temperature, salinity, hydrology) under controlled conditions, and, by so doing, test hypotheses regarding the regulation of habitat productivity. Similar habitats may be related to differences among parent estuaries.

4.0 Research Strategy

Development of the estuarine research program will follow a series of steps outlined in Figure 2. Important components are:

- Models[5] of interrelationships among factors mediating productivity within target habitats will be developed or adapted from existing information and analyses. The models will form a framework for studying each habitat type, and will provide a conceptual structure for planning experiments and testing hypotheses.
  - the nature and complexity of the models will depend upon the level of understanding of each habitat type; and
  - models may range from qualitative, descriptive formulations to quantitative or semi-predictive constructs.
  - models will be revised as new information is generated.
- Research on each habitat type will consist of the following approach:
  - local, multidisciplinary, site-specific field and laboratory experiments;
  - mesocosm[6] studies to integrate findings from local habitat/productivity studies and to test broader hypotheses on habitat functioning;
  - large-scale field manipulations (experiments) of estuarine habitats, where feasible and appropriate;
  - follow-up field evaluation studies.
- Several iterations of the steps may be required as knowledge about the functioning of target habitats increases and the sophistication of accompanying models improves.

In general, multi-year studies will be designed to quantify natural variability and to allow comparison of findings for different habitats within estuaries, as well as findings for similar habitats among estuaries. Undoubtedly, much of the variability observed for similar habitats may be related to differences among parent estuaries. In addition, ecological interaction among target habitats and adjacent habitats will be considered.

Investigations will lead to quantitative understanding of relationships between physical and biological factors that affect estuarine productivity. Results will be available at all stages of the effort and will permit environmental planners and managers to consider more thoroughly the impacts of alterations to estuarine ecosystems.

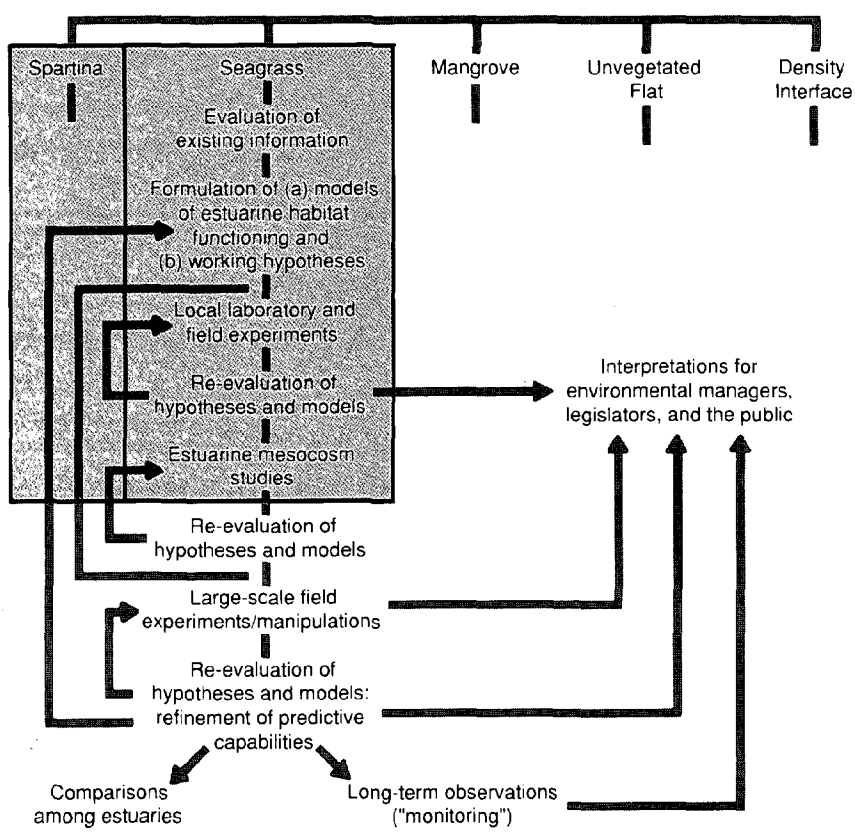
5.0 Synthesis

Two important aspects of synthesis for the estuarine science program are: (a) the use of models, at the habitat level, to direct research and integrate findings; and (b) the development of projections, on national and regional scales, of the impact of human activities on productivity, through modification and destruction of habitats and food webs. Associated with the latter will be efforts to evaluate the accuracy and precision of projections, and to recommend appropriate follow-up actions. Models will be used to structure and guide the direction of research. At least one model will be developed for each combination of supporting hypothesis and habitat type under study. The complexity of the models will reflect the levels of understanding of the processes being studied. In their most rudimentary forms, models may be conceptual frameworks for organizing information on processes that regulate estuarine productivity. More commonly, initial models may take the form of box models or material budgets such as for carbon, nutrients, or energy. Models of individual habitat types will be formulated early in the investigation; they will become more complex and increasingly quantitative as research progresses. *The goal is to develop quantitative understandings of habitat types that will permit predictions of changes in productivity that result from natural or human-induced changes in environmental conditions.* Figure 2 illustrates the progression of research and accompanying development of increasingly complex models.

Laboratory and small-scale field studies will be required to refine linkages among elements of the models. As models become more substantial and the ability to describe habitat functioning quantitatively increases, experimental studies may become more elaborate. In all cases, however, progress will be made through an iterative process that evaluates findings and reexamines the accuracy of models in light of new data. Research at several levels of complexity may be carried out simultaneously.

The progression of research will culminate in an observational program for evaluating the accuracy

Figure 2 Approaches for testing supporting hypotheses by habitat.



of predictions of habitat-associated productivity resulting from natural or human-induced changes. Evaluation of predictions is needed to ensure the accuracy of answers to fundamental resource management questions such as:

- What are the relationships between changes in land use and estuarine productivity;
- What are the quantitative relationships between estuarine primary productivity and productivity at higher trophic levels;
- What is the relative importance of major habitat types to fish and shellfish productivity;
- What are the implications to fish and shellfish productivity of alterations in the quality or quantity of estuarine habitats; and
- Can secondary productivity be protected or improved by managing for specific levels of primary productivity?

Emphasis will be placed on providing useful information–in useful forms–to managers. The information will be provided by supporting hypotheses and by habitat. Special care will be taken to ensure that adequate attention is devoted to synthesis of data and information, as well as to research.

[illegible]

Priority research will focus first on two of the habitats described earlier, seagrass beds and water column systems, in a cross-section of estuaries around the country. These habitats are extremely important because they:

- are critical to estuarine transport and productivity;
- are essential to the completion of early life history stages of economically-important species;
- occur in most coastal states; and
- are increasingly threatened by continued urbanization and industrialization of the coastal zone.

Research projects will address the four supporting hypotheses using the approach presented in Figure 2. Early efforts will consist primarily of: evaluating existing information; developing conceptual models and working hypotheses; and initiating field, laboratory, and mesocosm research. A list of potential research issues for each habitat is provided below.

Seagrass habitat:

- What are the consequential sources of fixed carbon in seagrass habitats? In what forms does the carbon occur and how is it used? How efficient and plastic are the paths linking primary production and production at higher trophic levels?
- What is the role of the physical structure in determining productivity of a seagrass bed? How plastic are rooted aquatics and benthic algae in filling this role?
- What are the time-scales, rates and magnitudes of natural and man-made changes in fresh- and saltwater inflow? How do these changes affect secondary production?
- To what degree is the carbon produced in seagrass beds utilized within these habitats? Are significant fractions sequestered within or transported from seagrass beds?

Water column habitat:

- What is the relative importance of "new" vs. "recycled" nutrients in water column systems? How do changes in the chemical form and rates of external nutrient inputs affect internal nutrient cycling? What temporal and spatial lags influence the expression of these inputs?
- Have man-induced changes in the number and composition of estuarine benthic or pelagic filter-feeding faunas affected overall secondary production? What is the significance of greatly enhanced microbial and microplankton populations in estuarine water column habitats?
- What is the role of density surfaces (pycnoclines and fronts) in mediating water column secondary production?

Studies undertaken to answer these questions will include measurement of:

- time variability of freshwater inflow, including measurements made during storms;
- nutrients;
- extent and nature of change of habitats in areas selected for study; and
- linkages of habitats to productivity, as functions of time.

Modeling of efforts will begin immediately to ensure that important pieces of needed information are identified early in the program to guide field studies. Research will address the nature of habitat changes as well as the rate at which such changes take place. This is important for modeling and for controlling mesocosm investigations. Other important considerations in design efforts relate to comparability of studies, particularly measures of productivity.

The estuarine research strategy will be implemented by NOAA's line organizations and OAR will play a major role in conceptualizing and conducting research.

NOAA's Estuarine Programs Office will coordinate the efforts, including distributing funds, developing a data management plan, and overseeing the

integration and synthesis of information collected by individual studies. Program research and synthesis efforts will be conducted through partnerships of NOAA components and academic institutions. The objective will also be to develop strong institution-to-institution relationships. The private sector also will be encouraged to participate in these partnerships. Competitive proposals for research and synthesis efforts will be solicited. After peer review and evaluation, selected studies will be initiated. A Review Committee will be established, under NOAA's Chief Scientist, to provide advice on program efforts. The Committee will review the program plan, target habitat types, and oversee the peer-review process.

The bulk of funding for the first and second year is to be used for field, laboratory, and mesocosm studies, with little funding allocated to administration or coordination. The Estuarine Programs Office will coordinate the effort and the line organizations will implement the program. Consequently, no additional administrative or managerial personnel will be required.

The relative involvement of NOAA line organizations will depend on the focus of efforts and results of the competitive process used to allocate funds. The major NOAA participants will be the Office of Oceanic and Atmospheric Research, the National Marine Fisheries Service, and the National Ocean Service, each in partnerships with members of the academic community. The relative balance between internal and external research will depend upon the results of the competitive process.

Data management will be largely a function of NOAA's National Environmental Satellite, Data, and Information Service. A management system will be established and maintained for the estuarine research program, in order to provide a central and accessible automated repository for program data and information. To accomplish this, it will be necessary to develop a data management plan that includes guidance on data submission consistent with those of NOAA and other federal agencies.

7.0 Overview

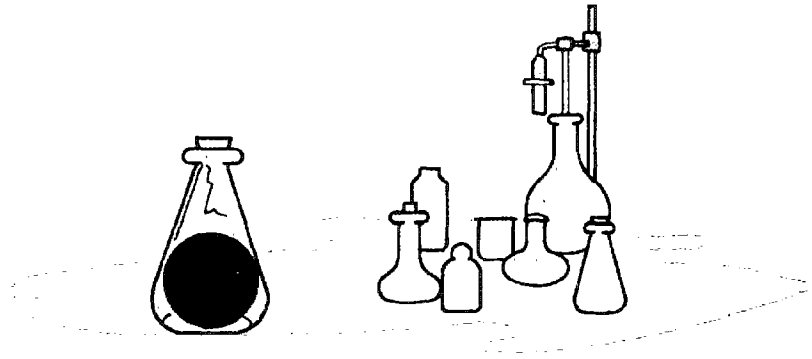
The proposed estuarine research strategy offers an opportunity to enhance understanding of processes that regulate and influence the magnitude and nature of estuarine productivity. Emphasis is placed on the study of target estuarine habitats (eg., *Spartina* communities, seagrass meadows, mangrove stands, unvegetated flats, and density interfaces). This approach complements more traditional studies that center on comprehensive investigations of single estuaries or that address the sources, fates, and effects of estuarine pollutants. While these sorts of studies are well-suited for basin-specific problems or local environmental management issues, they have not provided the quantitative information needed to *predict* impacts of man's activities on estuarine productivity.

Comparative studies of estuarine habitats form the core of the proposed investigations. Estuaries thus will be examined from a different perspective that will provide considerable insight into processes that are common to estuaries around the country. Ultimately, this approach also will provide the framework for interpreting and integrating findings from "case-history" studies of estuarine issues.

In summary, the estuarine research strategy will provide a generic understanding of estuarine productivity and provide critical knowledge needed to:

- predict the effects of human activities on estuarine productivity;
- restore and maintain critical habitats;
- restore and enhance fisheries;
- develop appropriate water management strategies; and
- develop cost-effective pollution control strategies.

This new knowledge and its use in management efforts will result in cost-effective regulation, improved permitting, and reduced litigation. The ultimate benefit will be enhanced economic development through wise use and management of estuaries.



Chapter VI

Marine Chemistry, Biology and Climate

Executive Summary

Problem and Opportunity

For many years the industrial nations of the world have been allowing large amounts of carbon dioxide and other "greenhouse gasses" into the atmosphere. Recent studies suggest that ozone and the marine sulfur cycle as well as carbon dioxide may have dominant roles in global climate change. Unfortunately the ultimate consequence, global climate change, can only be approximated. Because of the potentially severe consquences this lack of predictive precision could be disastrous.

Ozone in the atmosphere functions as an important oxidant, a precursor to highly reactive radicals, and as a significant absorber of ultraviolet and infrared radiation. The oceans are now thought to be not only a sink for ozone, but possibly a storage reservoir for ozone and a source of ozone precursors. Because of the absorption properties of ozone, pathways for production and destruction of this molecule need to be understood more fully if global climate changes are to be predicted accurately. The evidence to date implicates the ocean surface and the marine boundary layer as major contributors to these processes.

In yet another way, the oceans may play a major role in the modulation of world climate. Very recent data suggest a link between ocean productivity and climate, mediated by the marine sulfur cycle. Phytoplankton are a major source of volatile sulfur in the marine troposphere. Preliminary evidence suggests that fluxes of these compounds are correlated with precursors to cloud formations. This mechanism of biological regulation of climate is now a possibility that must be explored if global climate changes are to be accurately predicted.

These new advances only compound a problem that was recognized years ago. Carbon dioxide is in continuous flux, being added to the atmosphere through processes such as combustion of fossil fuels, chemical weathering of rocks, and decomposition of organisms etc. and being fixed, or removed from the atmosphere through formation of carbonate rocks, incorporation into organisms, and other processes. Present budget models of CO_2 are not adequate; in the end, the models always show a carbon deficit. The largest CO_2 "sink" appears to be the oceans. While the general areas where CO_2 is absorbed or released by the oceans is known, seasonal exchange cycles, rates, and the transport rates of CO_2 to the deep waters through advection or biological transport are still poorly understood. The ocean margins are one of the most biologically productive global areas and therefore important for fixation of atmospheric carbon. The ocean margins may account for some of the deficits seen. Carbon fixed by marine organisms in the coastal margins becomes part of the flux of particulates that gradually travel to the continental shelf to be buried in the sediments. Anthropogenic nutrient runoff may further augment fixation of CO_2 in coastal margins, thus increasing their importance.

Research Strategies

Only when the global climate models accurately include all the dominant variables can a complete

understanding, and hence a truly predictive model of global climate change be attained. To reach this understanding the research must concentrate on several levels in each of the areas that are thought to be important.

Ozone: *The magnitude of ocean sinks and the sources of ozone are the basis of the major questions that need to be addressed for a more complete understanding of the contributions of the ozone facet of climate research. Research to be conducted should include:*

- *Transport and distribution of ozone in troposphere including the marine boundary layer,*
- *The role of ocean productivity as a source of ozone precursors in the marine boundary layer,*
- *The possibility that the ocean stores ozone and releases it under certain meteorlogical conditions, thus becoming an ozone source.*

Carbon dioxide: *We need to understand the flux of carbon dioxide between the sea and air–particularly as a function of oceanic region and season, and over time as a result of past increases in atmospheric CO_2. This will help us predict change in the future. To fully understand these fluxes we need the following lines of research:*

- *Investigation of the invasion of anthropogenic tracers through the North Pacific thermocline at periodic intervals,*
- *Establishment of a series of oceanic sites for the ongoing seasonal measurements of tracer transient fluxes in key areas of the North Pacific from the tropics to the polar regions,*
- *Extensive study of a North Pacific CO_2 sink region.*

Additional important questions pertaining to carbon flux concentrate on determining the relative importance of carbon fixation and subsequent burial of that carbon in the regulation of tropospheric levels of carbon dioxide and the possible role of anthropogenic nutrient enhancement in accounting for the CO_2 deficits encountered in present carbon dioxide budget models. To answer these questions the following lines of research need to be pursued:

- *Examination of existing models to determine the knowledge needed to increase their applicability; using research results the model's predictions and adequacy can be tested,*
- *Identification of temporal trends of the variation in ocean circulation using synoptic, remotely sensed data,*
- *Determining the important processes involved in CO_2 fixation, particle development, settling, and transport of those particles through sampling regimes in coastal margin areas.*

Sulfur: *The role of sulfur in the global climate question needs to be examined. Although recent data imply a connection with volatile marine sulfur no definite causative relationship connects the two phenomena. Research efforts to determine the existence of a causative relationship and the magnitude of that relationship if it exists must include:*

- *Measurement of the concentrations of relevant sulfur compounds and cloud condensation nuclei, plankton speciation and productivity, cloud albedo, and other important oceanographic and climate variables,*
- *Determination of the physical, chemical, and biological variables that control planktonic production of these sulfur compounds,*
- *Identification and quantification of the reactions relating these compounds with the formation of cloud condensation nuclei,*
- *Production of models linking changes in ocean productivity, global albedo, and climate change. Essential questions of causative polarity and system stability can only be answered through the testing of such models.*

Why Now?

Since the start of the industrial revolution, atmospheric levels of carbon dioxide have been increasing due to the burning of fossil fuels. As the concentrations of CO_2 and other "greenhouse gasses" have increased in the atmosphere, a global warming is predicted. Estimates of CO_2 increases suggest that atmospheric levels are increasing at an accelerating rate. A global temperature increase of only one degree Celsius could have profound effects on the world climate. Atmospheric levels of "greenhouse gasses" are rapidly approaching the concentration sufficient to cause this increase. With new avenues of research now opened by the elucidation of possibly significant climate modulators such as ozone and sulfur, the probability of predicting potential destruction is greatly enhanced.

Benefits

The results of these investigations, if successful, will allow prediction of global climate change caused by

disturbances in the biogeochemical fluxes in the world oceans. In addition, the role of human induced increases in CO_2 concentrations can be better assessed. World food production, supply and demand for energy, all ecosystems, water resources, and human health can be significantly affected by even slight global warming. If these changes in global climate can be predictable, then preventative measures or informed preparations may be made to minimize the potentially drastic effects.

1.0 Introduction

In the last decade of the twentieth century, a paramount concern will be man-induced changes to our global climate. Research aimed at understanding, detecting, and predicting the causes and the consequences of climate change will engage much of NOAA's attention and resources. Opportunities exist for NOAA's marine chemists and biologists, both in the Environmental Research Laboratories and in NOAA's extramural programs, to contribute through their research to the world's efforts to cope with climate change.

Three areas of research are likely to engage NOAA's marine scientists as they address climate questions. The role that oceans play in the ozone cycle is poorly understood, yet understanding this role is essential if intelligent decisions are to be made on the regulation of ozone-destroying compounds. Within the carbon cycle, a good portion of man's fossil fuel emissions cannot be accounted for in either the atmosphere or in the oceans as inorganic carbon. A better understanding of the circulation of the oceans and the degree to which the carbon cycle is affected by ocean biology is needed if knowledge of the cycle is to be complete. Finally, recent research suggests the marine sulfur sources may contribute significantly to climate modulation by controlling open ocean cloud formation. The mechanisms that underlie this phenomenon need to be understood if the importance of marine sulfur emissions in regulating global climate is to be assessed.

2.0 Ozone

2.1 Ozone in the Marine Boundary Layer

Ozone has three important functions in the atmosphere. It is an important oxidant and the precursor for highly reactive radicals, particularly hydroxyl which is formed by the reaction of O(1D), produced by the photolysis of ozone with water. In addition, ozone is a significant absorber of ultraviolet and infrared radiation. The earliest view of tropospheric ozone assumed stratospheric injection and surface destruction with no intervening chemistry. A great many observations support these basic tenets of stratospheric injection and surface destruction.

However, it has now been demonstrated that a great deal of chemical production and destruction of ozone occurs in the troposphere, the rates of which sometime exceed the estimated transport fluxes. A combination of transport theory and chemical theory predicts ozone production in the upper troposphere and chemical destruction in the lower troposphere. Geophysical Fluid Dynamics Laboratory (GFDL) scientists have refined the transport model with a chemistry approach in an effort to understand the role of transport in determining ozone distributions in the troposphere. In their model, the sources of ozone are exchanged across the tropopause with chemical production occurring only in the upper troposphere. The results of their model significantly disagree with some observations. There is an apparent need for an additional 0_3 loss mechanism (in excess of the loss mechanisms already in the model) "corresponding to an equivalent desposition velocity of around 0.1 cm/s" in the boundary layer of the tropical and subtropical Pacific. The model also has high gradients of 0_3 mixing ratios and low surface 0_3 levels over land. In many cases the landsurface is a source of 0_3 and not a sink, whereas the ocean surface is still assumed to be a sink.

Current research by AOML scientists has focused on determining the magnitude of the oceanic sink for ozone. During a recent research cruise in the tropical Atlantic, AOML scientists observed an atmospheric ozone increase corresponding to an increase in marine biogenic non-methane hydrocarbons. Because of the reactivity of these hydrocarbons, their source region was probably within a few hundred kilometers. Within that spatial envelope, an increase in biological productivity was observed. The data suggest

a possible, but untested, cause and effect relationship between the biological productivity of the oceans and the formation of ozone precursors.

Production of ozone in the marine boundary layer is most likely to be through a complex series of photolytic and free radical reactions occurring in surface seawater and/or in lower portions of the marine boundary layer, involving biogenic hydrocarbons ranging from one to four carbons in size. Photochemical oxidation of these materials results not only in production of carbon monoxide (CO) and ozone, but also aldehydes, ketones, organic and, peroxyocyl nitrates, and aerosols. Methane is three orders of magnitude more abundant than the other hydrocarbons in the atmosphere, but it is one to three orders of magnitude less reactive than other hydrocarbons with OH radicals.

In addition to ozone precursors, such as methane and the non-methane hydrocarbons, the generally accepted mechanisms for ozone production require the presence of NO_x or organic nitrates in sufficient concentration. Measurements of NO_x in the remote Pacific indicate that the concentrations there are not high enough to support ozone production. However, measurements of NO_x mixing ratios in air masses on the Irish Coast and at Bermuda indicate that there should be sufficient NO_x to catalyze ozone production over the North Atlantic.

2.2 Research Strategy

2.2.1 Research Questions

OAR marine biogeochemical research on the ozone cycle is an integral part of the Radiatively Important Trace Species (RITS) program of NOAA. *The central marine question to be answered is what is the magnitude of the oceanic sink for ozone?*

Key questions that must be answered if this central question is to be resolved include:

- What are the spatial and temporal distributions of ozone sources in the marine troposhere, including the boundary layer?
- What role does the marine production of low molecular weight hydrocarbons play in the production of ozone in the marine boundary layer?
- What is the source of the nitrogen compounds required for ozone production in the marine boundary layer?
- Can the ocean store ozone as ozonide and release ozone under appropriate meteorlogical conditions?

2.2.2 Research Requirements

To determine the answers to the first two research questions, the magnitude of oceanic sinks and sources of ozone, research requirements are the following:

- To quantify the transfer rate of ozone from the free troposphere to the marine boundary layer by studying ozone fluxes at the free troposphere/boundary layer interface and on the downward side of convective circulation cells, to determine the scale over which this transfer rate is applicable, and to investigate whether turbulent processes and/or convective activity play a significant role in this transfer.
- To study under what conditions advective processes dominate the distribution of a chemical species like ozone in the boundary layer.
- To compare the strictly chemical destruction rate of ozone with the difference between the photochemical production and photochemical/chemical loss rate that occurs during the day.

There are two ways to arrive at an understanding of the magnitude of the oceanic sink. The first is to experimentally isolate a column of air from the sea surface to the top of boundary layer (over the tropical ocean that is assumed to be the trade wind inversion) and then measure the change in ozone in that column. The second way is to compute a columnar budget, i.e., quantify the fluxes as well as the steady state concentration. Neither of these is totally experimentally feasible at this time. The budget approach is the one that can be best addressed at this time.

This process can potentially be investigated through shipboard observations because it appears to occur below 30 m in altitude. Ship observations, however, cannot evaluate the other, supposedly larger source of ozone in the boundary layer, namely the free troposphere. However, aircraft such as the heavily instrumented NOAA WD-P3 can, because of sensors investigating vertical winds and turbulence, allow investigations of turbulent and convective transfer of ozone from the free troposphere to the boundary layer.

A comprehensive research program to determine the role of marine-derived low molecular weight hydrocarbons in the ozone cycle will require:

- The measurement of low molecular weight hydrocarbons in the marine boundary layer and the water column in selected oceanic regions.
- Determination of the pathways and mechanisms by which low molecular weight hydrocarbons

are produced and transformed in the marine environment.

This research program will require a close working relationship between physical, chemical, and biological oceanographers. A comprehensive program would consist of:

- A field program of research cruises that will undertake transects across regions of high and low biological productivity. Upwelling zones and the high latitude regions of the Atlantic and Pacific oceans at their peak times of productivity are of particular interest. A detailed program of chemical analysis and biological productivity measurements will be undertaken in the water column and the lower boundary layer as appropriate.
- A laboratory-based biological sources program that will be continued and expanded. Biochemical and biological experiments will be undertaken to determine the biological, chemical, and physical factors which control the production and fluxes of low molecular weight hydrocarbons from the water column to the boundary layer.

In current research at AOML, ozone is continually recovered at low levels when sea water samples are stripped with inert gases. It has been hypothesized that the source of this ozone is the decomposition of ozonide present in the water samples, and that the ocean may be serving as a storage site for ozone in the form of ozonide. If confirmed by additional studies, this phenomenon may represent an important new variable in the marine ozone cycle.

Necessary research activities needed to evaluate the significance of these preliminary laboratory observations include:

- Development of analytical techniques and methods for the direct measurement of ozonides in sea water.
- Retrospective analysis of GMCC surface ozone and meteorlogical data to assess the importance of the oceans as a direct source of ozone.

3.0 The Carbon Cycle

Estimates of the global carbon budget indicate that up to 47% of the fossil-fuel derived carbon cannot be ascribed to increases in the atmosphere. While some of the debate about the missing carbon is related to uncertainties in the estimate of the amount of CO_2 released from terrestrial land biosphere, the major sink for the missing carbon appears to be the oceans. Present estimates based on various box-diffusion models indicate that anywhere from 25 to 45% of the fossil-fuel-derived carbon resides in the oceans. The major causes of the present uncertainty in these estimates are the insufficient knowledge of physical and biogeochemical processes involving carbon in the oceans and inadequate treatment of these processes in ocean transport models. Improved accuracy in the estimates of the oceanic carbon uptake will undoubtedly rely on an improved understanding of essential physical and biogeochemical processes involving carbon and the development of ocean carbon models based upon more realistic general circulation models.

3.1 Role of Ocean Margins in Carbon Flux

Carbon in surface waters is fixed by photosynthetic processes to form organic particulates which sink into deeper waters. By far the largest fraction of this carbon is remineralized in the deep waters or on the seafloor. Estimates of the magnitude of this flux to deep water range from 2 to 6 gigatons of carbon per year. In addition to the large uncertainty in the marine biological carbon flux, the geographic distribution of the flux is still poorly understood. The contributions of the central gyres, the polar regions, and the ocean margins have yet to be resolved.

Of particular interest is the role played by the ocean margins (the regions between the coast line and the ocean boundary currents) in the carbon cycle. The margins are among the most productive areas of the ocean and are the regions where the stimulation of biological productivity by man's activities is most likely to have occurred.

Shelf regions represent the areas where very high rates of oceanic carbon fixation occur. As carbon fixation is dependent on the supply of nutrients, this results from transport of "new" nitrogen supplies (as opposed to nitrogen that is being recycled on a time scale of days) to the margin euphotic zone by various upwelling phenomena, onshore advection of deeper nitrogen-rich water, and from continental runoff. Measurements of carbon metabolism, production and exchange along food webs indicate that large fractions of organic matter produced on continental shelves is exported to continental slopes and to the deep ocean. This transport occurs as fine particle flux which is in turn modulated through processing of the fixed carbon into larger particles, i.e., grazing of

phytoplankton by zooplankton and the concomitant metabolism and "packaging" into fecal pellets particles and/or aggregates.

Recent evidence indicates that this transport may be significantly enhanced through filaments of high pigment (carbon rich coastal waters which extend into open ocean currents, e.g., the California Current, the Gulf Loop Intrusion, or by mesoscale eddies such as warm core eddies formed by the Gulf Stream along the Eastern shelf of North America). However, a significant portion of shelf carbon may be "trapped" on continental slopes. This is especially possible for that portion of carbon fixed via new nitrogen from continental runoff since this carbon would be fixed on the inner shelf and require a longer transport time time to the shelf edge, thus giving time for grazing and other processes to increase particle sizes and form aggregates that would settle on the slope.

Supplies of essential nutrients have increased markedly in coastal runoff since the advent of the industrial revolution. This anthropogenically driven nutrient enhancement may well be responsible for enhanced productivity in the ocean margins and increased export of carbon to continental slopes. This transport and subsequent burial and diagenesis in slope deposition centers could represent "missing" carbon in global carbon dioxide budgets. As an example of the enhancement of coastal ecosystem nutrients, an increased nitrogen transport in the Mississippi River system during the period 1937 to 1980 has been documented. There is also evidence of increased coastal productivity resulting from this flux as shown by the documentation of seasonal hypoxia associated with high chlorophyll levels down current from the Mississippi Outflow. Similar enhancements of coastal productivity may be occurring in areas such as the New York Bight, the Chesapeake Bay and flow plume, and the Rhine (as evidenced by high pigment levels in the southern North Sea), etc. However, the lack of adequate spatial data on decadal time scales for any such systems prevents quantification of the extent of enhanced carbon fixation or export. It is clear that no similar enhancement of productivity has occurred in the open ocean and that analyses of abiotic storage of carbon dioxide (vertical mixing, polar sinking) cannot account for all of the carbon dioxide emitted by fossil fuel burning. Anthropogenic nitrogen loading to the coastal ocean would allow export of 1.5 gigatons deposition centers of carbon per year, via fine grained sediments, from the shelf to deposition centers on the upper slopes. If half of this amount represents increased loading since the industrial revolution it accounts for missing carbon in unbalanced chemical and biological budgets for global carbon dioxide, i.e., 0.7 to 1.6 gigatons of carbon per year.

Two key research questions to be addressed if the carbon cycle is to be fully understood:

- Is carbon fixation in the ecosystems of the ocean margins and subsequent burial in shelf sediments an important factor in the regulation of global tropospheric levels of carbon dioxide?
- Does the additional carbon fixed due to anthropogenic nutrient inputs account for the "missing" carbon in the unbalanced (chemical and biological) carbon dioxide budgets?

A multidisciplinary OAR research program will be developed to identify and quantify the important physical, chemical, and biological processes so as to allow their inclusion in models of global ocean flux and climate.

Through enhanced monitoring of nutrient flux to the coastal ocean and coastal productivity (both *in situ* and via remote sensing), much can be done to provide an adequate data base, in space and time, to allow assessment of potential carbon export from ocean margins. However, specific, intense studies of carbon fixation and the subsequent food web processes which package and metabolize this carbon must also be conducted synoptically with physical studies of transport, sediment dynamics, and benthic processes. This will allow assessment of the amount and rate of transport as well as of the eventual fate of the fixed carbon. It is also reasonable that shelf depostion centers of particulate carbon should be evaluated in terms of their existence and extent and whether or not such storage is temporary (steady state) with an eventual transport to deep ocean sediments, or permanent. The following types of studies are necessary to supply our understanding of the processing of carbon in the ocean margins. The proposed program can be considered to have four components.

- A modeling component which will serve to guide the other program components toward a predictive capability with an ultimate product of

enhanced global climate models in which the ocean modulation of tropospheric CO_2 is properly parameterized.

- A time series component which will generate data on temporal trends in the productivity of ocean margins and nutrient inputs to nearshore waters which is reasonably synoptic with data on variations in ocean circulation. Circulation data coming from other global research efforts, e.g., WOCE.
- An experimental component conducted in selected ocean margin areas to elucidate the important processes involved in ocean margin CO_2 fixation, such as particle development, settling, and transport so that these processes can be quantitatively included in the models.
- A remote sensing component which will allow a real application of the results of the other three components and generalization of these results to global models.

Interagency and international aspects: An OAR Ocean Margin Global Ocean Flux Study will be a integral part of the U.S. Global Ocean Flux Study. The ocean basin portion of GOFS is being organized and sponsored by the National Science Foundation Ocean Margin GOFS; this would also be an important part of the international J-GOFS program, organized to bring together the resources and abilities of the international community in addressing the role of ocean biology in the carbon dioxide cycle and climate regulation.

While the potential for increasing atmospheric levels of CO_2 from combustion of fossil fuels to cause a global warming has been recognized for some time, only very recently has the comparable climatic significance of other greenhouse gases been realized. The new NOAA initiative RITS specifically addresses only the atmospheric measurement of the global trends and distributions of these other climate-linked gases. Very recent work suggests that the limiting uncertainty in predicting the warming scenario for our planet during the next decades to century may not be in the uncertain growth rates of the greenhouse gases in the atmosphere, but rather in the very poorly understood circulation processes in the upper ocean, where the heating transient is being temporarily stored. This ocean thermal lag is greatly delaying the approach of our atmosphere to radiative equilibrium with its changing trace gas composition. Thus, the role of the ocean is crucial in setting the warming rate, even though the ultimate equilibrium temperature of the global system will be determined by the atmosphere.

While atmospheric CO_2 time-series began during the International Geophysical Year (IGY), and atmospheric measurements of trends and distributions of other greenhouse gases have been initiated during the past decade, corresponding time-series and distributions of CO_2 and other climate-linked trace gases in the sea are very sparse or nonexistent. Excepting some pioneering work on tritium in the North Atlantic, ocean model interpretations of chemical tracer fields in the thermocline are completely lacking, though such studies clearly offer the best hope of defining the timeframe for the predicted global warming. The transient is occurring now, so the need for the measurement of the evolving chemical tracer fields in the upper ocean tnd their use in improved ocean-atmosphere models is an opportunity that should be grasped.

Fossil-fuel derived CO_2 enters the ocean surface via gas exchange processes and is ventilated downward by mixing and thermohaline circulation. Deep convective mixing of the water column takes place in winter in the polar and subpolar regions which provide transport pathways for advection of heat, CO_2 and other tracers into intermediate and deep water masses. The newly formed water masses spread laterally along isopycnal surfaces. By coupling high precision and accurate CO_2 measurements with chemical tracers, such as chlorofluorocarbons, ^{14}C and ^{3}H, it will be possible to improve our understanding of the role of intermediate and deep water mass formation and related processes in CO_2 uptake, and for constraining future general circulation models.

The seasonal variations of carbon-nutrient relationships and tracer chemistry in the oceans are poorly known. Recent studies by PMEL scientists indicate that wintertime gas exchange and mixing processes play a major role in the transfer of CO_2 and chlorofluorocarbons in the subpolar regions of the North Pacific. Corresponding information for other oceanic regions is very sparse. However it is known that intra- and inter-annual variations (i.e., El Nino) can be very large, especially near the equatorial zone where the oceans are a major source to the atmosphere. With the development of general ocean circulation models which include CO_2 uptake and release, there will be a major requirement to include

seasonal variations of CO_2 and other tracers to verify model simulations of seasonal changes in CO_2 sources and sinks.

Air-sea exchange of CO_2 across the air-sea interface is probably the major rate limiting step for CO_2 uptake in the oceans. The strong and non-linear dependence of gas exchange on wind speed suggest that, if the physical parameters influencing gas exchange are well characterized, gas exchange rates may be predicted with good accuracy from satellite scatterometers. Experimental studies of CO_2 and other trace gas exchange rates under varying open-ocean windspeed cinditions are needed to provide a more realistic estimate of regional gas exchange rates.

3.2.1 Research Strategy

3.2.1.1 Research Questions

Major questions that need to be answered are:

- What is the flux of carbon dioxide between the sea and the air as a function of oceanic region and seasons?
- In what way has the natural distribution of regional CO_2 sources and sinks already been altered by the 25% increase in atmospheric CO_2 during the past one-hundred fifty years?
- How will the present regional distribution of air-sea CO_2 fluxes change in the next century in response to much higher atmospheric levels and climatically induced ocean/atmospheric CO_2 levels and climatically induced ocean/atmospheric circulation changes?

3.2.1.2 Research Requirements

To address the research questions listed above will require both a field program of experimental measurements and a modeling program. Advances in analytical methodology, especially in the precision of sea water inorganic carbon measurements, now hold out the possibility that the invasion of fossil fuel CO_2 will be detectable over the coming years. The measurement of CO_2 and dissolved inorganic carbon, along with the freon tracers, is then an essential part of the observational program. The field program will consist of these major activities:

- Chemical snapshots of the invasion of anthropogenic climate gases (CO_2, freon) throughout the North Pacific thermocline from the Aleutians to the equatorial upwelling zone. The snapshots will be taken at five-year intervals. The survey will be conducted with such a spatial coverage that all the major features of the CO_2 distribution are adequately contourable and that the resulting chemical snapshot serves as a reference state against which future changes in circulation and/or chemical composition might be reliably detected.
- The establishment of ocean carbon time-series sites in the North Pacific Ocean to follow seasonal and interannual variablility in CO_2 fluxes will be established. These sites will cover the polar, semitropical gyre, and upwelling regions of the North Pacific, thus including waters which are major sources and sinks of CO_2.
- An international, focused study of the CO_2/freon sink region in the northwest Pacific off Kamchatka in cooperaton with WOCE. In addition to the above, a modeling component will be required to guide the optimal sampling of the marine carbon system and thereafter to interpret the resulting measured CO_2 distributions in terms of present and future CO_2 uptake capacity of the sea.

Interagency and international aspects: An OAR tracer field study will be closely linked to WOCE, the World Ocean Circulation Experiment, to the Global Ocean Circulation Experiment,to the Global Ocean Flux Study, and to evolving programs such as Global Tropospheric Chemistry. Much of the fieldwork will be conducted in phase with WOCE.

4.0 Sulfur

4.1 The Global Sulfur Cycle and Climate

The Gaia hypothesis, as proposed by Lovelock and Margulis in the early 1970's, states that life has regulated and stabilized the environment of the earth, keeping it within narrow bounds that allows the continuation of life. This hypothesis considers the lower atmosphere as part of life itself, and argues that plant and animal populations regulate certain aspects of this atmosphere, including temperature and chemical composition.

This hypothesis is controversial and has not won widespread acceptance, partially due to the inability to test examples raised in its support. Now, however, in the marine sulfur cycle, there appears to be a degree of climate regulation which is consistent with the Gaia hypothesis and is also testable. The year 1987 saw significant amount of evidence published

in support of the marine sulfur cycle providing a mechanism for a link between oceanic productivity and climate. Among the facts and calculations which have appeared in the recent literature are the following:

- The major source of volatile sulfur in the remote marine troposphere is from the production of dimethylsulfide (DMS) by marine phytoplankton.
- There may be a possible direct correlation, in the remote marine atmosphere, between the rate of DMS flux and the number of cloud condensation nuclei.
- There is an apparent direct correlation between the amount of daily solar radiation and the rate of DMS flux from the ocean surface.
- There is only a very weak correlation between conventional measures of primary productivity and DMS flux rates.

From the above information, a new hypothesis has been postulated: that the natural biogeochemical cycle of sulfur in the marine environment constitutes a negative feedback loop that may modulate global warming. The hypothesis essentially states that the major source of cloud condensation nuclei (CCN) over the oceans is non-sea salt sulfate aerosol. This aerosol is an oxidation product of planktonically produced DMS. Because the reflectance (albedo) of clouds (and thus, the earth's radiation budget) is sensitive to CCN density, biological regulation of climate is possible through the effects of variations in solar insulation at the sea surface and through the physical oceanographic forcing functions acting on the planktonic production of DMS.

There is a very poor understanding at present of the hypothesized marine sulfur cycle. While negative feedback has been postulated as operating within the current global climate regime, evidence from 20,000-year old antarctic ice suggests a positive feedback loop may have operated during the past ice age. This ice contained a higher than average number of particles derived from DMS, with possibly concomitant higher numbers of CCN, higher cloud albedo, and a resultant drop in temperature. It is not at all clear what the impact of global warming by CO_2 emissions will be on the volatile marine sulfur cycle and subsequent marine cloud formation.

The volatile marine sulfur cycle, then, may play an important, but as yet, poorly defined role in climate regulation. Understanding global climate requires that the volatile marine sulfur cycle and its climate regulatory role be thoroughly studied.

4.2 Research Strategy

4.2.1 Research Questions

The key research question that must be addressed is what, if any, role does the volatile marine sulfur cycle play in the regulation of global climate? Important subsidiary questions include:

- What are the controls on distribution of DMS producing plankton species?
- What are the important factors that control DMS emission?
- What is the relationship between atmospheric DMS and CCN in the remote marine atmosphere?
- What impact does changes in CCN in remote marine regions have on cloud cover and global albedo?
- What role is played by anthropogenic sulfur emissions?

4.2.2 Research Program

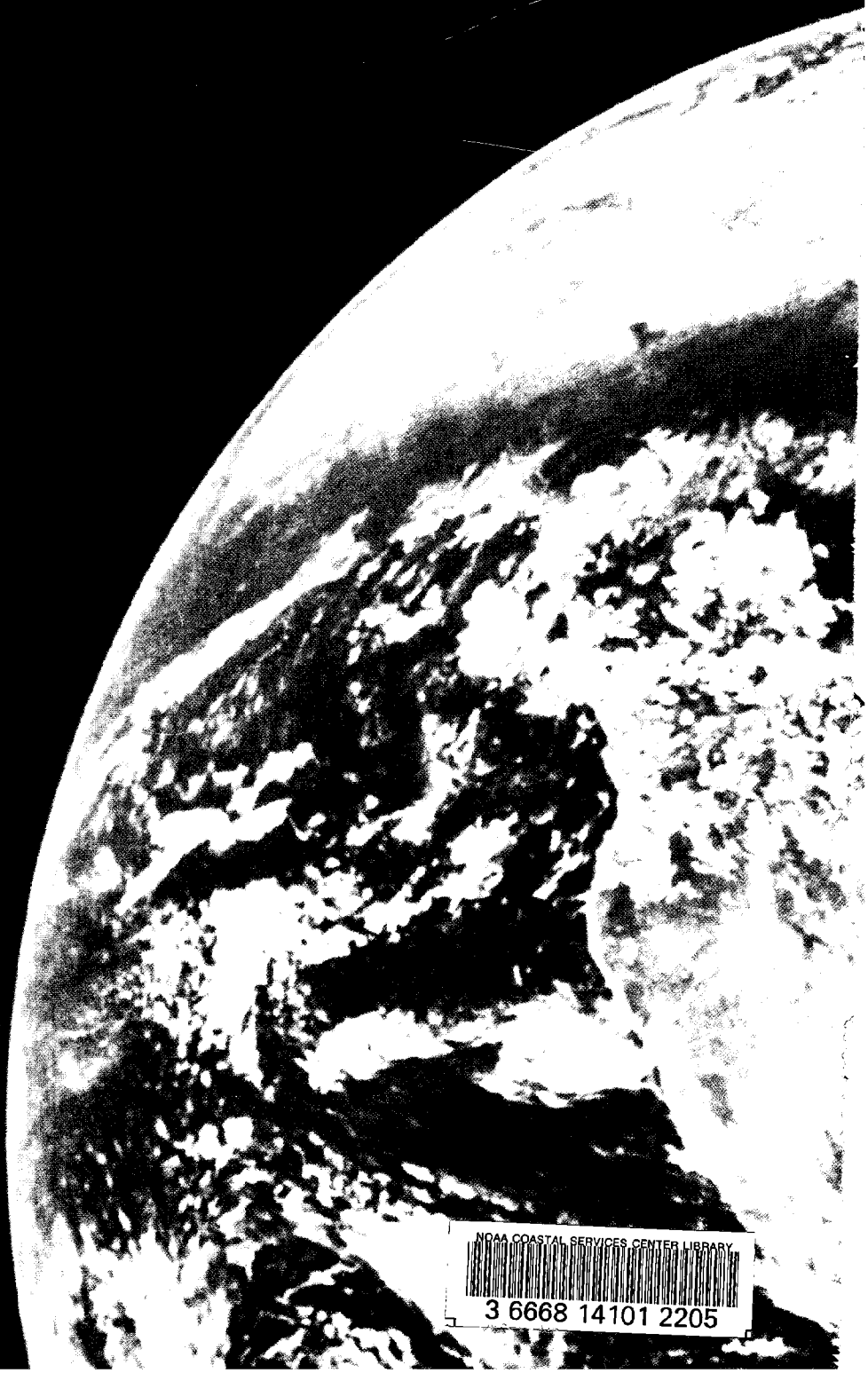
The proposed program will have the following elements:

- A field component which will, through ship cruises and aircraft overflights, measure key sulfur species and CCN concentrations in the marine troposphere, plankton speciation and productivity, cloud albedo, and other important oceanographic and climate variables. Measurement will be made on a seasonal basis from the tropics to the polar regions to define the impact of the volatile marine sulfur cycle on climate.
- A laboratory component to determine the physical, chemical, and biological variables which control DMS production by marine phytoplankton.
- A laboratory component to identify and quantify the reactions which relate DMS to CCN.
- A modeling component to link changes in ocean productivity, global albedo, and climate change. Essential questions of the polarity of feedback and system stability can only be answered through the development and testing of predictive models.

5.0 Summary

If we are to have any hope of reasonabaly predicting the directions, rates, and consequences of global climate change, we must understand the critical interactions of the oceans and the atmosphere. Physical oceanographers have been conducting extensive research programs on this subject in recent years and, as a consequence, are making major progress in understanding such phenomena as the periodic El Ninos. Circulation and climate modelers, utilizing these research results, are beginning to develop models with realistic chances of simulating these events as first steps towards predictions of climate variation and change.

We have a much poorer understanding of the chemical interactions between ocean and atmosphere. The tools to develop such an understanding are available or are being rapidly developed at the present time. There is a ready opportunity for NOAA, through the programs described above, to take the lead in addressing major research problems in understanding the influences of the carbon, ozone, and sulfur cycles and how these cycles impact, in turn, affect our global climate. The programs described above are unique but are important portions of multiagency, international efforts in global marine chemistry as they relate to global cycling and change. They are appropriate for NOAA to undertake and consistant with NOAA's role and mission.



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