A Unified Plan for Ocean Science

A Long-Range Plan

for the

Division of Ocean Sciences

of the

National Science Foundation

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Advisory Committee on Ocean Sciences

August 1987

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August 24, 1987

Dear Colleague:

On behalf of the Advisory Committee for Ocean Sciences (ACOS), I am pleased to transmit the 1987 revision of the Long-Range Plan for the Division of Ocean Sciences (OCE).

The concept and outline of the plan was initiated by the ACOS in 1983. The Committee, working closely with the OCE staff, developed a Long-Range Plan (LRP) to identify needs and priorities for ocean research and research infrastructure. The LRP, completed in the spring of 1984, was favorably reviewed by the Board on Ocean Science and Policy of the National Research Council that summer. The Plan was adopted at the ACOS meeting in May, 1985.

At the same time, ACOS laid the groundwork to revise the LRP every two or three years and established an ACOS Subcommittee to lead that effort during 1986. The Ocean Studies Board again reviewed the draft LRP in 1986. The revised LRP was approved by ACOS at the May, 1987 meeting.

The long-range planning activity has extended over several years, led by several ACOS chairs with contributions from many members and OCE staff. Particular thanks go to Vera Alexander and Bob Corell who preceded me as chair and to the ACOS members whose names appear on the attached list.

The budgetary framework embodied in this version of the LRP reflects actual funding availability only through FY-87. Beyond that, it projects funding levels that in the committee's view, represent optimum opportunities for scientific advancement. It does not, and is not intended to, reflect NSF endorsement of the LRP and the concomitant funding levels.

On behalf of the ACOS, I am grateful for wide-spread interest and support throughout the community and for the opportunity to submit this Long-Range Plan for Ocean Sciences.

Sincerely,

Brian T.R. Lewis,
Chairman

BTRL/saf
Enclosure

Advisory Committee on Ocean Sciences, 1983-1987

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Executive Summary

Knowledge of the oceans and continental margins has expanded dramatically in recent years bringing insights about the oceans and their role in the complex processes that govern the nature and health of our planet.

This Unified Plan is the product of a science that has matured extraordinarily during the past decade and that is poised to address scientific questions of vital national interest. The Plan is based on the following premises:

- Progress in the ocean sciences requires a mix of fundamental research, including both small projects and multidisciplinary large-scale research that connects the sciences of the ocean, atmosphere, and solid earth.
- Ocean sciences, together with the other geosciences, can expand our knowledge of the interrelationships at work around the globe by describing how the component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve in the future.
- Essential technologies and techniques to exploit the potential of the ocean sciences are becoming available and proven, particularly earth/ocean observing satellites, computer systems, and advanced methods and sampling systems.
- The National Science Foundation, together with the academic ocean community, should continue to craft long-range plans and strategies for ocean research that recognize national scientific interests and that build upon a community consensus concerning research trends and priorities.

The Plan sets forth a unified approach for the Division of Ocean Sciences of the NSF. It highlights, in three parts, a global program in oceanic and ocean lithospheric research.

Section I describes the underlying need for an NSF-supported ocean science research program that addresses priority global scale research initiatives and core programs of research in the ocean science disciplines.

Section II develops the unifying themes of the ocean sciences and presents a detailed projection for the global interdisciplinary ocean sciences research programs and for the fundamental core discipline-based research programs. It also details the vital importance of support for an infrastructure of modern and efficient ships and platforms, advanced technology, new equipment and facilities, and an aggressive international program in Ocean Drilling. The essential ingredients are:

- **The Core Program** - Priorities for this Core Program are outlined for the four disciplinary aspects of the ocean sciences (i.e., biology, chemistry, geology and geophysics, and physical oceanography), for the Ocean Drilling Program, and for advanced programs in oceanographic technology. Further, Critical Needs are outlined for the future in the core programs, including constructing and refitting research vessels for scientific operations, facilities, new technology, post doctoral training, biotechnology and ODP sample analyses.

- **The Global Program** - Plans for NSF-supported Global Ocean Studies and Global Ocean Lithosphere Studies are described, both as components of NSF's Global Geosciences Program, and as parts of a program to study global change. These are seen as contributions to international efforts such as WOCE, WCRP, GOFS and IGBP. The Global Ocean Studies focus research on global ocean circulation, climate, and productivity; open ocean fluxes; coastal ocean dynamics and fluxes; ecosystem dynamics and recruitment mechanisms; and the land/sea interface. The Ocean Lithosphere Studies focus on ridge crest processes and on tectonics and structures of submerged continental margins.

Section III presents a program plan and prospectus for each major program component of the Ocean Sciences Division of NSF. Long-range planning priorities are recommended for the:

Physical Oceanography Program;
Chemical Oceanography Program;
Biological Oceanography Program;
Marine Geology and Geophysics Program;
Ocean Drilling Program;
Oceanographic Technology Program; and
Ship Operations, Shipboard Scientific Equipment,
and Ship Construction/Conversion.

The Plan includes information on recent, present, and planned NSF ocean sciences budgets. It details FY 1989 through FY 1996 budget perspectives by program areas and program elements. The budget outlined is designed to present an aggressive Ocean Sciences Program, consistent with overall NSF strategic planning guidelines and with the vital contribution that these sciences can play in the nation's science policies and interests.

Section I

Global Ocean Research: A Time for Action

In the rapidly evolving ocean sciences, new data, ideas, models and methods are bringing previously unrecognized phenomena to light providing us with new perspectives on interrelationships on our planet. This new global perspective has also brought a fuller realization that the processes regulating conditions on Earth are delicately balanced and easily perturbed.

Growing human populations affect the land, air and water worldwide. The global food supply depends critically upon climate. Carbon dioxide released into the atmosphere by burning fossil fuels is changing the earth's temperature. While the oceans will eventually absorb much of this material, it will not happen soon enough. Therefore, we need a much better understanding of the consequences. How do changing rainfall patterns affect farm fertility? How soon will polar ice caps melt and how much will sea level be raised?

The monsoon has long been recognized as a control on the success of the harvest in India and Southeast Asia. Now it appears that the monsoon is controlled by an atmospheric phenomenon called the Southern Oscillation, which in turn controls El Niño in the ocean off Peru. El Niño is best known for devastating Peruvian fisheries in 1972 and 1982-83, but its effects are more far reaching. The 1982-83 El Niño has been blamed for disrupting ecosystems as far away as the Gulf of Alaska, triggering ravaging storms on the west coast of North America, drenching the U.S. "sun-belt" with unusually heavy rains, and leaving a thick snow pack in the Rocky Mountains that later produced heavy flooding in Colorado. Accurate forecasts reduce damage from such events.

Metal-rich deposits forming at ocean ridges and on seamounts may be an important source of strategic metals, such as cobalt. Models of their formation provide clues to the location of similar deposits on land, yet the processes forming such deposits are largely unknown.

The largest untapped resources of hydrocarbons are located on submerged continental margins. Their detection and recovery require understanding the processes which form the margins. As United States hydrocarbon reserves decline, it is imperative that the science underpinning discovery and recovery of new resources be pursued.

The need for a more unified global perspective is compelling. Modern ocean science is a sophisticated and quantitative endeavor that draws upon and influences the fundamental sciences. *Physically*, as a turbulent fluid, the ocean provides input to development of the dynamics of nonlinear mechanical systems and shares the complexities of these systems. *Chemically*, the numerous reactive molecules, compounds, and ions in solution tax the limits of analytical skills and the understanding of rates and equilibria. *Biologically*, the diversity of organisms and complexity of their interrelationships within the marine biosphere present challenges for development of new models and techniques applicable to organismal, molecular, and evolutionary biology in general. *Geologically*, ocean studies provide the key to understanding past climates, the formation of many mineral resources, the causes of major earthquakes, and the evolution of the oceans in the context of a dynamic earth.

Although oceanography is by nature an interdisciplinary science, the greater part of marine research over past decades has been traditionally segmented into programs focused on one or another of its component disciplines. Recently the disciplinary lines have begun to dissolve and growing attention to interdisciplinary studies has produced some dramatic progress. The problems now at hand call for even greater interaction among ocean scientists. Although focused disciplinary research remains essential, substantial increases in integrated efforts are now imperative.

Developing the Unified Approach: The Work to Be Done

Some pathways to a global approach are clearly indicated. We must better define ocean circulation, its associated physical processes, and the biological, geological, and chemical consequences. General circulation patterns, their variabilities, dynamics, associated boundary interactions, and resulting fluxes must be studied more intensely with programs designed to determine global and mesoscale patterns. Data from dedicated field experiments addressing the dynamics of the general circulation with its major current systems (Gulf Stream, Kuroshio) will help to define the general circulation, including large-scale mean fields and basin interconnections.

The ocean and atmosphere form a tightly coupled system that largely controls the earth's climate and its variability. The ocean plays two important roles: heat storage and transport of heat and water. Intermediate and deep waters, by their heat content, reflect air-sea exchange processes extending over periods ranging from years to centuries. A better grasp of air-sea exchange on a global scale will advance our understanding of the earth's climate-control systems.

Ocean currents exert a major control over distributions and fluxes of materials in the sea. Elements and compounds such as carbon, nitrogen, sulphur, phosphorus, water, biogenic gases, and man-made aerosols all have important roles in complex global cycles. The magnitude of the exchanges in these cycles is virtually unknown. Inputs from human activity mark many of these cycles and may serve as useful tracers for the processes involved. Some of man's waste products can themselves modify the global systems. For example, the build-up in atmospheric carbon dioxide since the beginning of the Industrial Revolution has caused a worldwide rise in temperature and possibly in sea level as well.

Chemical cycles and physical processes must be understood if we are to interpret the biological structure and dynamics of the world ocean, including primary and secondary production, recruitment of populations, predation, and decomposition. The general relationship between oceanic physical processes and marine ecosystems has long been recognized, but only in the last few years has enough been learned to address specific problems. We are just beginning to comprehend the effects of large-scale ocean phenomena (such as El Niño) on marine ecosystems.

At the same time, studies of processes on smaller spatial and temporal scales are essential to a better understanding of large scale phenomena. Modern approaches to these studies may include large experimental ecosystems (mesocosms) to examine the cycling of biologically important materials and the role which key predators play in structuring pelagic communities. Other important, but poorly understood, processes which operate at intermediate temporal and spatial scales include the distribution, recruitment mechanisms, and trophic relationships of invertebrate and fish larvae.

Coastal regions are only a small fraction of the total volume of the ocean, but they exert a disproportionate influence upon it. Human activities have the greatest impact in this zone. But the interaction goes both ways - conditions in the coastal zone can also have great influence on human activities. Most rivers enter the sea through estuarine zones, complex, highly variable regions that often show immense biological productivity. Each is distinct, and each modifies the material passing through it in its particular fashion. Many coastal zone organisms range far and influence open-ocean communities. Natural and man-made materials washed or blown from the continent either settle and interact with the biota or move out to sea. The resultant fluxes of chemicals, particles, and biota represent boundary conditions that must be defined if we are to understand the ocean system.

In the surface layer, plankton convert dissolved materials into a vertical flux of particulate matter. As particles sink, consumption, decomposition, and chemical exchanges (dissolution and adsorption) modify their original composition. Much of the particulate matter returns to solution at various depths as it falls or is eaten, digested, and excreted. Some fraction of the particulate mass, still reactive, reaches the bottom. Chemical and biological modifications occur within the sediments. To a large extent, the sediment particles themselves consist of the remains of planktonic organisms. Their organic components are progressively degraded as bottom dwellers consume them, but a small fraction of the organics may persist and eventually become petroleum. The skeletal remains mostly redissolve, but some endure and survive burial to become a part of the sediment where they record the ocean's history over millions of years.

The thick sediment deposits along the continental margins form a significant repository for products of ocean-continent interaction. Understanding the distribution and history of these deposits provides temporal constraints on chemical, biological, and particulate fluxes, as well as a guide to the evolution of biota, climate, and oceanographic conditions during their formation. The deepest sediments along passive continental margins record the earliest history of new ocean basins created by continental rifting and seafloor spreading. Ocean drilling provides access to the deep sedimentary layers in the margins and ocean basins and the crustal rocks beneath them.

Deep-ocean ridge crest processes are responsible for the chemical and thermal properties of hydrothermal vent systems. These systems are important as sources and sinks for chemical elements in the oceans and are responsible for extensive sulfide mineralization. They provide unique habitats for vent communities. Through seafloor spreading, ocean ridge systems create and modify 70% of the earth's crust. A comprehensive understanding of the processes that control the dynamics, structure, composition and variability of these systems is required.

The Geosciences: A New Global Initiative

The scientific issues and global perspectives of the ocean sciences are critical components of the tightly connected ocean-atmosphere-geosphere-biosphere system. Taken together, they form a major new initiative within the National Science Foundation known as the Global Geosciences Program, begun in FY 1987. This effort, in which ocean sciences play an integral part, consists of separate but related research efforts and treats the earth as an integrated system of physical processes. It encompasses the full range of earth sciences and includes global tropospheric chemistry, properties of the solid earth, dynamics of global ecosystems, and features of global ocean and atmospheric circulation and biogeochemical fluxes as well as their relationship to climate variability.

The Global Geosciences Program is designed to examine four components of the global system - atmosphere, ocean, biosphere and solid earth - and includes seven programs of study:

Global Tropospheric Chemistry,
World Ocean Circulation Experiment (WOCE),
Studies of Interannual Variability of the
Tropical Ocean and Global Atmosphere (TOGA),
Global Ocean Flux Studies (GOFS),
Global Ecosystem Dynamics,
Ocean Lithosphere Processes, and
Remote Sensing of the Solid Earth.

The Global Geosciences Program was born of a gradual evolution of the sciences involved, major advances in observing systems, and the advent of supercomputers. Since the early 1980's, attention has focused on studying the environment within a planetary context. Large-scale complex feedback mechanisms operate among the fluid, living, and solid components of the Earth system. They must be more completely understood in order to address such fundamental issues as climatic change and predictability, changing carbon dioxide concentrations, acid rain, and the exchange of heat and biological species within the atmosphere, ocean, and biosphere.

The NSF Global Geosciences Program is the keystone of a national effort to improve fundamental understanding of global change which is being coordinated with other Federal agencies. This effort, referred to as a "Scientific Program of Research into Global Change", will benefit from a series of other activities recently completed or now underway. For example, the Office of Science and Technology Policy (OSTP) has completed for the President an review of the applicability of space-based remote sensing to study of the earth system. The National Academy of Sciences is establishing a new standing committee to address problems related to global change.

Internationally, components of the NSF Global Geosciences Program are already contributing to major global studies being sponsored by the International Council of Scientific Unions (ICSU) in cooperation with intergovernmental organizations such as the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of Unesco. The NSF TOGA program organized by ICSU and WMO as a part of the World Climate Research Program (WCRP). Similarly, the NSF WOCE program is a driving force in the planning of the WCRP's international WOCE program.

The International Geosphere-Biosphere Program (IGBP) being developed by ICSU is likely to rely heavily on the efforts underway under GOFS to provide a sound basis for its planning. The International Lithosphere Program will clearly benefit from the results of the NSF program for study of Ocean Lithosphere Processes. These international efforts, to which the NSF Global Geosciences Program will be a major contributor, provide an opportunity for truly integrated studies of the earth's environment necessary to establish the basis for effective management of the world's resources and protection of the global environment.

Utilizing Modern Technology

Availability of new methodologies account for the rapid pace of the ocean sciences in recent years. Future progress depends upon continuing development of techniques in exploration, measurement, and comprehension. An important role will be played by greater availability of laboratory-based instrumentation such as electron microprobes, ion probes, electron microscopes, ultraviolet laser Raman spectrometers, accelerator mass spectrometers, and liquid chromatographs, and also by a growing arsenal of sophisticated shipboard water samplers and measuring instruments.

For example, biologists are deploying new sampling systems ranging from highly instrumented nets with twenty square meter openings to ship-board flow cytometers and towed underwater multi-frequency acoustic sonar systems for studying plankton. Geologists have benefited from new developments in long-range side-scan sonar systems, a constant series of advances in multichannel seismic surveying and signal processing, cryogenic magnetometers, long-coring systems, ocean bottom and near ocean bottom instruments and survey vehicles. Submersibles have provided a first glimpse of unsuspected seafloor biota and processes; surely much remains undiscovered.

Remote sensing methods (acoustic mapping of water masses and airborne - especially satellite-based observations) are revolutionizing our understanding of ocean systems. Measurements can be made simultaneously around the world of sea surface height, temperature, plant pigments, winds, and ice cover. Combined with in situ (surface and deep ocean) observations and with subsurface interpretive models, remote sensing provides a quality and quantity of information impossible to obtain a short time ago. But the resulting flood of information threatens to overwhelm our ability to assimilate it. High-speed data-transmission networks are required to distribute the flow of measurements, to make them accessible to researchers and to permit large data sets to be incorporated into models of ocean phenomena. Supercomputers and related facilities are critically important to digesting and interpreting this wealth of data.

Expansions in computing capability are producing yet another revolution in ocean science. Numerical models offer a powerful tool for increased understanding. As supercomputers become more accessible, models can become more sophisticated, less abstract. For instance, our new global view provides a better understanding of how the atmosphere affects the ocean. By comparing these models with actual ocean behavior, scientists can modify the models to better represent the ocean and to quantify its influence on earth's climate. Thus, continued expansion in computational power is a key ingredient in the new global ocean science.

Expanding the Effort

Scientific progress tends to be erratic. Occasionally, developments in basic understanding or technology coalesce to produce dramatic advances. Such a breakthrough is now in prospect. A balanced national program of interdisciplinary, global perspectives and traditional focused projects will provide a new vision of the earth-ocean-atmosphere system. A major increase in global geosciences research with an interdisciplinary approach exploiting new technology will produce a tremendous increase in our understanding of the earth system.

In the United States, the NSF is the lead agency for research in ocean science. Through its commitment and allocation of resources NSF provides leadership, guiding the growth and evolution of ocean science. As such it has the responsibility to foster the planning required for the continued development of ocean science in the nation's academic institutions. The Foundation involves the ocean scientific community in its planning and funding activities. NSF workshops and studies solicit advice from advisory groups and panels, including the Advisory Committee for Ocean Science and the National Research Council's Ocean Studies Board. NSF interacts and coordinates work with other agencies (ONR, NASA, NOAA, DOE, EPA, USGS, etc.), relating fundamental research to national needs and policy.

The Division of Ocean Sciences has recognized the need for and accepted responsibility for fostering advancement and unification of ocean science. It has, through its Advisory Committee, formulated in this report a plan for a decade of rapid progress.

Section II
A Unified Plan
A. The Ocean Sciences
Core Research Program

The Division of Ocean Sciences supports research through two Sections. The Research Section funds investigations in Biological, Chemical, and Physical Oceanography, and Marine Geology and Geophysics. The Oceanographic Centers and Facilities Section underwrites Ship Operations, Oceanographic Technology, and the Ocean Drilling Program.

A unified plan for growth in Ocean Sciences must recognize that new research initiatives arise from the core programs and their support for relatively small projects in traditional disciplines. This core has critical needs that should be addressed to allow the individual investigators access to improved facilities and analysis techniques, to train new Ph.D-level scientists in these technological innovations, and to undertake new research beyond that called for in the Global Geosciences initiatives, such as in marine biotechnology and ocean drilling core analysis.

The Physical Oceanography Program is concerned with understanding the circulation of the major oceans and adjacent seas, continental shelves, estuaries and large lakes. Investigators study physical properties, water boundaries, and the driving forces, such as winds, solar radiation, precipitation and evaporation, the earth's rotation, and tides. The program is divided into five areas: ocean circulation, coastal and estuarine circulation, ocean/atmosphere coupling, surface and internal waves and tides, and microstructure and turbulence.

The Chemical Oceanography Program supports scientists who seek to understand processes affecting the chemistry of oceans, estuaries, and large lakes, and the way they respond when perturbed. They study processes and mechanisms affecting chemical compounds and phases in the ocean to determine routes and rates of supply to and removal from the ocean as well as alterations during transit. The program is divided into five areas: equilibria and physiochemical properties; transfers and transformations at the land/sea boundary; material fluxes, transport, and alterations; the influence of biochemical processes; and development of tracers to study large-scale processes.

The Biological Oceanography Program has wide responsibilities involving the support of scientists to study and predict relationships among marine organisms and their interaction with geochemical and physical processes. A central focus is to understand ecosystems ranging from ocean margins and continental shelves to central gyres and ocean basins, and ultimately to understand the role of organisms in global-scale processes. Biological oceanography involves research into primary production; microbial loop processes and the role of microorganisms as sources and sinks of materials and nutrients; higher trophic levels and food webs; and communities adapted to specialized, extreme environments.

The Marine Geology and Geophysics Program includes work on the composition and evolution of oceanic crust, deep ocean basins, and continental margins; the distribution, composition and history of terrigenous and biogenic sediments on the seafloor; and the history of the oceans. Research methods include seismic reflection and refraction; magnetic studies of the crust and sediments; analysis of gravity data; petrologic and geochemical study of ocean crustal rocks; paleontologic, mineralogic, and geochemical analyses of marine sediments; and studies of samples recovered by the Ocean Drilling Program.

The Ocean Drilling Program is an international effort to explore the structure and history of the earth beneath the ocean basins and margins using the drilling vessel *JOIDES Resolution*. Samples are analyzed aboard ship along with results from logging, other downhole experiments, and regional geophysical field studies to address important problems. These include crustal evolution, crustal structure, and hydrothermal systems at midocean ridges; tectonic and sedimentary history of passive and active margins; origin of island arc systems; response of marine sedimentation to sea level changes; global mass balance of sediments; history of ocean circulation (paleoceanography); and evolution of marine organisms.

The Oceanographic Technology Program provides funds for Ocean Sciences research activities in three distinct areas: shipboard technician support, acquisition of shared-use scientific instrumentation, and new instrument development.

The Ship Operations Program provides funds for the operation and maintenance of research vessels used by NSF-funded scientists. This includes funding for crew and marine staff salaries; maintenance, overhaul, and repair; insurance; direct operating costs such as fuel, food, supplies, and pilot fees; shore facility costs directly related to ship operations; and indirect costs.

The Shipboard Scientific Support Equipment Program provides funds for ship equipment deemed essential to the proper and safe conduct of ocean science research. This includes such items as deck, navigational, and communication equipment.

The Ship Construction or Conversion Program supports new ship construction, conversion of ships to research vessels, and remodeling and refitting existing research ships.

Areas of Critical Need for the Core Programs

The program described above has developed through proposal pressure and scientific judgement to make the most of limited basic research funding. Examination of future research opportunities indicates that this core program should grow in several areas. Some of this growth involves increases in research support for specific subdisciplines, while most program areas require improved support to introduce new technology, train future scientists, and facilitate processing of data. All three of the latter activities are common to all of the sub-disciplines.

Technology Development and Support: New instrument and vehicle capabilities can both accelerate progress in ocean sciences and render its operations more cost effective. It is essential to bring new concepts into reality and assure their effective use through technical support centers serving large segments of the community; an example is projected development and support of an accelerator mass spectrometer center for isotope studies. It is important to upgrade geochemical analytical capabilities with new generation instruments (electron microprobes, ion probes, mass spectrometers, etc.) and to provide physical oceanographers with modern current meters, instrumented current-tracking floats, and acoustic current-measuring systems (tomography, multibeam doppler). Biological oceanography requires continued development of new sampling and analytical tools (acoustic and optical sensors, flow cytometry, satellite remote sensing, mid- and shallow-water submersibles, and remotely operated vehicles).

Establishment and Operation of Essential New Facilities: The effectiveness of ocean sciences research would also be enhanced by establishment of several new support facilities. The principal need is for an essential data and communications network offering a selection of hardware/software options for accessing satellite and other data, for building local data archives, and for interactive processing, analysis, and interpretation of these data. There is a related need for an ocean modeling facility to provide high-quality supercomputing capability for large data sets. In order to take advantage of recently developed capabilities to take long undisturbed cores from the seafloor, a long-core facility should be established to fill the gap between standard piston coring and the continuous cores obtained by the Ocean Drilling Program.

General Facilities Improvement: Enhanced support is required to upgrade and renovate the generally decaying and outmoded shorebased infrastructure, including buildings and facilities at academic institutions and coastal laboratories. This is needed not only to ensure the continued productivity of the core programs but also to provide facilities essential to the success of unified ocean science initiatives.

Postdoctoral Program: The vitality of ocean sciences requires not only that we maintain our community through graduate education but also that we bring new skills and viewpoints into areas such as numerical modeling, satellite imagery, and multichannel seismics. An expanded postdoctoral program would be the best way to meet this need.

B. The Global Program

The first NSF Long-Range Plan for Ocean Sciences (released in late 1984) outlined two new initiatives -- a Global Ocean Study and an Ocean Lithosphere Study. The essential elements of these two were later combined into a single initiative, the Global Geosciences Program (included in the NSF FY 1987 budget). It brings together related research efforts of the Ocean, Atmospheric, Polar, and Earth Sciences Divisions. Areas of inquiry include studies of global ocean and atmospheric processes and circulation; biogeochemical fluxes and their relationships to climate variability; global tropospheric chemistry; the properties and dynamic processes of the solid earth; and the dynamics of global ecosystems. This program also includes studies of global ecosystem dynamics and of interaction between the geosphere and biosphere undertaken by the Division of Ocean Sciences in cooperation with NSF's Division of Biotic Systems and Resources.

This revised and updated Long-Range Plan builds upon that initiative and outlines the essential ocean sciences components of the Global Geosciences Program and its contribution to major national and international studies of global change. For consistency with the original Plan, the two global initiatives detailed here are called "Global Ocean Studies" and "Ocean Lithosphere Studies."

These programs enable NSF to focus its resources and contribute to critical national and international research programs such as the World Climate Research Program (WCRP) and its World Ocean Circulation Experiment (WOCE); the International Geosphere-Biosphere Program (IGBP); and Global Ocean Flux Studies (GOFS). Each of these is referenced in the relevant sections below and in the detailed programmatic information contained in the appendices.

While multi-investigator, coordinated programs will be required to implement these major initiatives, the programs listed above are not necessarily synonymous with the initiatives or their components described below. Several coordinated programs may be appropriate under a given topic; such programs might be conducted simultaneously, sequentially, or both. Several components of the initiatives are closely related; thus, a single research program could be relevant to more than one component. Furthermore, smaller research programs, including many conducted by individual investigators, will also make significant contributions to these initiatives.

Initiative 1. GLOBAL OCEAN STUDIES

There are five components or subinitiatives within this initiative: Global Ocean Circulation, Climate, and Productivity; Open Ocean Fluxes; Coastal Ocean Dynamics and Fluxes; Global Ocean Ecosystem Dynamics and Recruitment; and the Land/Sea Interface. Detailed descriptions of each follow.

Global Ocean Circulation, Climate, and Productivity

Continuing developments in satellite remote sensing, numerical modeling, biological sampling, acoustic tomography, and transient tracers present opportunities for major advances in our understanding of the oceans. The research combines synoptic global-scale information from satellites (TOPEX, ERS-1, NROSS, and others) on oceanic dynamic topography and wind forcing stress with data from ships on ground truth, properties and dynamics in the underlying water column, and distribution of transient tracers.

Integrating these activities with additional satellite-derived data (ocean color imager) and associated field programs provides information on ocean productivity, its spatial and temporal variability, and the underlying causes of this variability. Global productivity estimates are critical to ocean flow studies described later. Closely coupled to these observational aspects are numerical modeling efforts using general circulation models of the ocean and/or atmosphere systems to help guide the field activities and data analyses.

The extensive field observation programs range in scale from a number of smaller process-oriented studies to integrated national and international field efforts being developed for the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean/Global Atmosphere (TOGA) Programs.

Some of the scientific questions to be addressed are:

- What is the mean, large-scale circulation of the oceans, its variability, and the resulting heat transport? How much of it is predictable?
- What are the large-scale coupling mechanisms (wind stress and thermodynamics) between the oceans and atmosphere which relate to El Niño/Southern Oscillation and other elements of the global climate system?
- What is the effect of the global circulation and its variability on primary productivity of the open ocean?
- How do distributions of chemical tracers vary in time? What do these variations reveal about large-scale vertical mixing, surface ventilation, deep circulation rates, and the ocean's role in controlling the global CO₂ balance?

The major elements of these programs are:

- spaceborne oceanographic sensors to provide global and regional surface boundary conditions;
- computational resources including augmentation of staff, communications, and related NCAR costs for handling the oceanographic share of the advanced vector computer (AVC), and equipment at oceanographic institutions for high data-rate links with NCAR and other supercomputer centers;
- preparation for and implementation of in situ field measurements including development and testing of equipment and techniques, initiating selective long-term baseline time series, and global field measurements utilizing both shipboard sampling and moored and drifting arrays; and
- analysis and numerical modeling based on development and use of global circulation models and analysis procedures that can utilize real-time satellite and in situ data sets.

Incremental funding in FY 1989 will augment planning and data management activities as well as TOGA-related process studies. It will also support CTD and tracer sampling, modeling/analysis studies, and continuation of instrument development efforts. Augmented support for TOGA-related studies and initiation of a two-year preparation period for global circulation and productivity studies will require \$40M and \$51M in FY 1989 and FY 1990, respectively.

Activities will include instrument development and acquisition; establishment and operation of institutional data analysis centers and communications networks with NCAR and the Jet Propulsion Laboratory; expanded transient tracer, long-lines, acoustic tomography, and biological productivity studies; and field and modeling activities associated with monsoon research involving both U.S. and Indian oceanographers. Full-scale field operations in concert with satellite sensing (altimeter, scatterometer, and ocean color imager) and numerical modeling will cost about \$50M per year during FY 1991 to FY 1995. Ship and facilities costs are included.

Open Ocean Fluxes

A major goal for ocean sciences over the next decade will be to understand oceanic biogeochemical cycles and budgets at large space and long time scales. Depiction of the physical dynamics (steady state and first order variability) essential to meeting this goal will be obtained through global ocean circulation research programs such as WOCE. The character and primary productivity of the sea surface will also be evaluated synoptically from satellite sensors. Finally, the lateral flux from the coastal boundary zone must be understood and integrated into a comprehensive global ocean flux study (GOFS).

A most exciting opportunity exists to link these boundary conditions and new knowledge of ocean dynamics with intensive in situ observations of the fluxes of soluble and particulate phases and the transformations among them. New tools and techniques, e.g., sediment traps, large-volume samplers, experimental benthic chambers, chemical buoys, and numerical modeling, will be developed and used in conjunction with physical and satellite observation over the next ten years. This program will provide an understanding of the factors which control long-term biogeochemical dynamics at ocean basin and global scales.

Some of the major scientific questions to be addressed are:

- What is the magnitude of oceanic primary productivity ? How does it vary with time?
How is primary productivity controlled by physical processes?
- How much of this production represents recycled material and what are the processes and pathways involved in this recycling?
- What are the flux rates of organic matter from the photic zone into the ocean interior in relation to primary production?
- What are the transfer rates between soluble and particulate phases within the water column and what processes are involved?
- What are the flux rates between the ocean and the seafloor?

The major elements of this initiative are:

- Ocean color imagery and other satellite-derived data which provide global and synoptic sea-surface boundary conditions;
- Further development of critical sampling technology to measure or infer material fluxes in the ocean system over a wide range of time and space scales;
- Extensive field observation programs focused on critical processes, regions, and/or time periods and ultimately integrated with satellite-derived surface boundary conditions; and
- Development of modeling capabilities for global fluxes in the context of improved general circulation models of the coupled ocean-atmosphere system.

The incremental costs of this program total about \$70M between FY 1988 and FY 1992. Major emphasis during this period would be in planning, data analysis, technology, numerical model development, and pilot experiments for testing system integration and defining observational requirements. This would phase into long-term global observational programs starting in FY 1993 and costing about \$25M annually. This full-scale phase would be closely coupled with satellite observation programs on surface productivity and circulation as well as with coastal boundary observational efforts. Ship and facility support costs are included.

Coastal Ocean Dynamics and Fluxes

The other major component required for a study of global ocean flux is scientific understanding of coastal oceanography for dealing with pollutant dispersal and fisheries management and for understanding the influence of climate and weather. The coastal ocean is also a most significant environmental boundary zone - a temporary sink for materials eroded from the continents, a mixing pot for river outflows and marine waters, a region of high biological productivity, and a source for much of the dissolved and particulate material flux to the open ocean. The developing technical and conceptual ability to study this region as an integrated physical, chemical, and biological system provides a significant, long-term opportunity to advance our understanding of the dynamics of coastal regions and the fluxes of material through them. Coordinated investigations under the Land/Sea Interface Program will provide information on the interconnections of land, fresh waters, and estuaries that is needed for studying inputs to the coastal ocean.

Some scientific questions to be addressed are:

- How do winds and atmospheric pressure fields, mean currents, bottom topography, river outflow, and internal shelf waves interact with one another to form the continually evolving mosaic of surface currents, upwelling centers, eddies, and jets?
- To what extent can these rapidly changing currents be forecast and what parameters require monitoring for such forecasts?
- How do the geographical setting and physical dynamics quantitatively influence particulate and dissolved matter, the seafloor, and biological productivity and evolution in coastal and estuarine regions?

- What is the flux of dissolved and particulate material brought into this boundary zone by rivers and carried out across shelf areas to the deep ocean? How do these fluxes vary from place to place, with time, and as a result of biological and chemical alteration processes?

The major elements of this initiative are:

- Multicomponent, multidisciplinary field programs in representative coastal regions;
- Extensive use of satellite imagery (physical dynamics from altimetric, scatterometric, and infrared temperature measurements; primary production from the ocean color imager) and airborne remote sensing (wind stress, infrared and color imagery, and air-dropped XBTs) coupled with *in situ* physical, chemical, and biological observations;
- Development of rapid biological sampling techniques and tools to analyze distributions and productivity on time and space scales appropriate to those of the relevant physical and chemical processes; and
- Development and expanded use of computers and computer modeling in handling large data sets, guiding the field programs, interpreting data, and assessing the system's predictability.

Funds required during FY 1988-92 average about \$16M per year and will support the design and implementation of several pilot field experiments to test the integration of a diverse suite of new sampling technologies and the ability to quantify dynamic processes and flux measurements. Full-scale field programs based on the results of these pilot experiments will follow in FY 1993 at a cost of about \$24M per year. Ship and facilities costs are included. A remote-sensing research aircraft will be required for this initiative beginning in FY 1989. It will also benefit the other global ocean studies.

Global Ocean Ecosystems Dynamics and Recruitment

Over the next decade, one of the most practically important and scientifically challenging areas of marine research is that of recruitment of marine organisms. Age-classes of nekton and benthos frequently vary in abundance by orders of magnitude, usually due to variable survival of larval or juvenile stages. Climate, physical factors, and variability in primary production, secondary production, and predation have been hypothesized to regulate nekton and benthos age-class success. We are now at a point in the development of the field where many of these basic recruitment mechanisms can be studied effectively.

Some of the major questions to be addressed are:

- How do climate, physical and chemical processes, and biological constraints interact to influence recruitment of invertebrates and fishes?
- How important is the role of predation on young stages as a determinant of future population structure and which are the important predators?

- What are the salient differences in recruitment patterns and their causal mechanisms in high- and low-latitude systems?
- Under what conditions is recruitment and subsequent ecosystem structure more likely to be physically (transport, temperature, etc.) or biologically (starvation, predation, etc.) mediated?
- How is recruitment related to nutrient availability and primary production? How is variability at the primary producer level expressed in production and ecosystem dynamics at higher trophic levels?

Major aspects include:

- Developing a broader understanding of the annual and seasonal variability and productivity of ecosystems and the effect of ocean climate on such variability;
- Expanding collaborative research by physicists and biologists at a variety of scales to learn how larvae, their predators, and their prey are aggregated and dispersed;
- Use of new sampling, identification, and data analysis methods to bring the plankton studies into the same time frame as important physical processes;
- Determining the kinds and abundances of predators and their rates of predation on planktonic or young stages of nekton;
- Application of emerging technologies, including in situ sampling from research vessels, mesocosm studies on larvae-zooplankton interactions (feeding, predation), acoustic methods to estimate abundance of larvae and zooplankton, and satellite methods for assessing primary production and its variability;
- Developing and applying numerical models to guide experimental research and predict how physical processes and nutrient availability influence recruitment potential; and
- Developing coherent theory regarding evolution of adaptive strategies by marine organisms which enhance the long-term survival of their populations.

Incremental support growth averaging about \$3M annually for FY 1988-93 should provide the basic underpinnings for our understanding of plankton dynamics, larval ecology, and predation as they collectively influence recruitment variability and higher trophic level productivity. This growth will also allow development and experimental use of new technologies and methodologies. Major, long term field experiments based on this developmental work will be conducted in the mid-to-late 1990's and cost \$20-25M annually. Ship and facility costs are included.

Land/Sea Interface

This is the newest program of Global Geosciences and is a cross-directorate effort involving the Division of Biotic Systems and Resources of the Biological, Behavioral and Social Sciences Directorate (BBS) and the Biological and Chemical Oceanography Programs of the Division of Ocean Sciences. It is part of Global Ecosystem Dynamics within Global Geosciences.

Interfaces between land and ocean are only a small part of the earth's surface, but they are of great global importance in terms of biological productivity, geochemical processes, origin of sedimentary rocks, and the evolution of life. Human activities have already wrought significant changes upon the interconnections of land, freshwater, and the coastal ocean. Furthermore, these couplings are highly sensitive to changes in global climate.

As a result of land- and water-use practices, flow volumes of many of the world's rivers have been significantly altered. Their content of dissolved and particulate substances has changed, resulting in two- to fivefold increases in river nutrient levels in developed regions during the latter half of this century. Such changes are also likely to be occurring in developing countries as a result of deforestation, population growth, and wider use of fertilizers.

Present day coastal environments are the product of relatively stable sea level conditions over the last 7,000 years. The widely-predicted atmospheric warming could cause a rapid rise in eustatic sea level at a rate of perhaps more than one centimeter per year in about fifty years. Significant melting of polar ice could raise sea level several meters more in the next century. Global climatic changes may dramatically alter regional temperature regimes and precipitation (and, consequently, runoff) patterns. These changes may, in turn, influence terrestrial, freshwater, and coastal marine ecosystems and their biota.

Some major questions to be addressed are:

- How do modifications in the flux of materials from land to rivers and from rivers, wetlands, and estuaries to the coastal ocean, caused by complex interactions of global and local human activities, affect aquatic and marine ecosystems and global biogeochemical processes?
- Do these changes have significant implications for the global carbon budget?
- What will be the effects of global climate changes, including changes in temperature, precipitation, and sea level rise, on aquatic and coastal ecosystems and on the large human populations that live in these environments?

The major elements of this initiative are:

- Utilization of the new generation of satellite sensors to provide visualizations and promote computer modeling of these environments as integrated systems;
- Integrated studies of fluxes of materials within watersheds and receiving estuaries and the biological responses to variation in these fluxes;

- Greater development of the role of coastal marine laboratories and field stations as national resources whose centers of environmental research activities are already at the land/sea interface; and
- Expansion of the Long Term Ecological Research (LTER) program of NSF (currently within the Division of Biotic Systems and Resources), to cover more representative types of land/sea interface systems; and broadening of their concept to include recognition and monitoring of the effects of global change on regional ecosystems through the utilization of products of other Global Geosciences programs.

The Biotic Systems and Resources Division (BSR) and Biological Oceanography Program are beginning to fund some community planning activities in FY 1987. BSR plans to significantly expand this function in FY 1988 (\$.5M). By FY 1989, the Ocean Sciences Division (principally Biological and Chemical Oceanography) require \$1M, increasing to at least \$10M within five years.

Initiative 2. OCEAN LITHOSPHERE STUDIES

The Ocean Lithosphere Studies Initiative includes two components: (1) Ridge Crest Processes and (2) Tectonics and Structures of Submerged Continental Margins.

Ridge Crest Processes

Fundamental questions about ridge crest processes remain unresolved because of a lack of long-term observational data to test hypotheses and predictions. The subjects needing intensive study include the driving forces of plate tectonics; thermo-mechanical properties of the oceanic lithosphere; and hydrothermal, volcanic, and mineralization processes at ridge crests and their geological, chemical, and biological effects. Extensive application of a newly developing suite of observational systems over the next ten years will yield much new information and a deeper understanding of these basic elements of earth science.

Some of the major questions to be addressed are:

- How does the ocean lithosphere respond mechanically to large surface loads, to compression, to bending, and to stretching? With an understanding of these factors, what can we learn about deeper processes in the earth, such as mantle convection, by looking through the "ocean lithospheric window?"
- What are the driving mechanisms for seafloor spreading? How does crustal accretion vary with time? What are the local scales of accretion and tectonics in space and time? How are volcanic processes coupled to hydrothermal circulation at midocean ridges? What are the controlling factors on sulfide mineralization and the extent of deposits? How does oceanic crust vary and how is it altered as it moves off-axis?
- What are the chemical and thermal properties of hydrothermal fluids from vents and what is their role in the mineralization process? What is the contribution of vent fluxes to the chemical balance of oceans? What chemical reactions occur? What is the relation between fluids and biologic communities?

- Are vent communities controlled by such factors as nutrients, heat, or symbiosis and, if so, how? How do vent communities colonize in new areas? How do such communities adapt to unique chemical surroundings, high-temperature, and high-pressure environments? What is the physiology and productivity of vent organisms?

The major elements of this initiative are:

- Improved capabilities in multichannel seismics (MCS) and their expanded use in selected areas with experiments focused on determining the thermo-mechanical properties of the oceanic lithosphere under varying conditions of age and stress/strain. ODP crustal drilling and downhole experiments for direct physical measurements will augment this work.
- Increase in number of field programs with modern detailed survey capabilities to determine history and scale of crustal accretion. Development of integrated geological, chemical, and biological studies using research submersibles for representative sites - e.g., high- and low-temperature, seamounts, sedimented and unsedimented sites.
- Development of in situ instrumentation for long-term monitoring of hydrothermal vents and crustal accretion - e.g., flow meters, chemical and thermal sensors, strain gauges, seismometers. ODP drilling on the rise crest region will provide depth control from downhole instruments.
- Long-term integrated biological program to understand the unique properties of vent organisms with emphasis on chemolithotrophic bacteria, symbiont hosts, substrates used for energy, and physiological adaptations. This will define community structure, life history strategies, and evolution of biological communities.

Incremental funding will provide essential upgrading of existing capabilities, expanded and integrated use of new, multichannel seismic, side-scan sonar, Seabeam and submersible systems, and development and implementation of a long term ridge crest/hydrothermal vent monitoring program. Ship and facility operational costs are included.

Tectonics and Structure of Submerged Continental Margins

Continental margins not only form the boundary between the two major physiographic provinces on our planet, but also, in many cases, are past or present boundaries of the lithospheric plates that make up the earth's surface. A much deeper understanding of the structure, tectonics, and dynamic evolution of these fundamental geological features is within our grasp. It can be realized with extensive application of multichannel seismic tools, with development of new and more powerful techniques to use these tools, with long coring capabilities, and with ocean drilling at carefully selected margin sites, ultimately using a riser capability.

Some of the major questions to be addressed are:

- What geologic units underly active and passive continental margins? What are the dominant tectonic, geochemical, and thermal processes involved in creating ocean-continental boundaries?

- How do lithospheric structures vary along continental margins, including old and young margins, island arc and trench regions, fast and slow convergence sites, and thick and thin sedimentary sequences? How are they related to adjacent geologic provinces, onshore basins and tectonics, and offshore basins and trenches?
- What causes initial rifting? How are conjugate sites on the opposite sides of ocean basins related? What are the controlling factors for subsidence rates, sediment accretion rates, thermal histories, and regional basin formation?

The major elements of this initiative are:

- Expanded seismic experiments to determine the deep structure in contrasting regions and integration of these data with lithologic, acoustic, stratigraphic, structural, and subsidence analyses, and also with heat flow, gravity, and magnetic measurements. Onshore geologic studies of the continental lithosphere should be correlated with offshore drilling by the Ocean Drilling Program.
- Utilization of state-of-the-art seismic and other geophysical field systems with sufficient resources to maintain effective data acquisition and data analysis centers. Attention must be given to maintaining a critical mass of scientists, technicians, and students for these operations.
- Support for riser drilling on continental margins to determine the age and composition of the basement in order to identify seismic reflectors and biostratigraphic data needed for subsidence models and composition and facies of the geologic section.

Incremental costs will cover modest upgrades of existing academic facilities and support the essential use of these capabilities through the next decade. They also cover coordinated, community-wide use of state-of-the-art industry exploration capabilities. Developmental and operational costs of riser drilling are included under facilities support in the FY 1989-93 period.

Funding Requirements

A summary budget for Ocean Sciences and component budgets for each Program are provided in the tables of Section IV.

Section III ***Program Areas***

A. Physical Oceanography Program **Long-Range Planning**

I. Core Program

The Physical Oceanography Program is concerned with developing a basic understanding of the circulation of oceans, estuaries, and large lakes. Investigators document water properties and study the motions of water masses and transport processes. They seek to understand the physical properties and boundaries of water masses and the driving forces, such as wind, solar radiation, precipitation, evaporation, the earth's rotation, and solar and lunar tides. The program has been traditionally divided into five topical areas: ocean circulation, coastal and estuarine circulation, ocean/atmosphere coupling, surface and internal waves and tides, and microstructure and turbulence. The heart of the program is the general circulation of the ocean, complementing the central thrusts of the NASA and ONR programs in surface and upper ocean processes, respectively, and the coastal zone programs of MMS, NOAA, Corps of Engineers, and state agencies.

Recently the major thrust of large physical oceanography projects has been in tropical oceanography. This reflects the rapid development of theoretical models of equatorial circulation and the recognition that, first, these ideas could be tested with observations and, second, atmospheric general circulation seems most sensitive to the condition of surface waters near the equator.

The near-term direction for physical oceanographic research seems relatively clear based on recent theoretical and technological developments. At least two recent theories of mid- and high-latitude ocean dynamics, namely, ventilation of the main thermocline and the homogenization of potential vorticity, are ripe for further development and testing. Remote sensing techniques (acoustically tracked floats, satellite altimeters and scatterometers, surface drifting buoys) make global sampling possible on meso, synoptic, and gyre scales. Expanded large-scale computing capability and improved ocean circulation models provide new tools for data assimilation and interpretation. The need for improved understanding of ocean circulation for climate studies has stimulated development of two large-scale projects in the international scientific community - the Interannual Variability of the Tropical Ocean and Global Atmosphere Project (TOGA) and the World Ocean Circulation Experiment (WOCE).

II. Critical Needs of the Core Program

The categories of critical needs specified in Section II.A all apply to the Physical Oceanography Program. Those which have a significant impact on development and maintenance of basic research capability in physical oceanography in the immediate future are described below in greater detail.

1. A Postdoctoral Program in Numerical Ocean Modeling. The national supercomputing initiative has three thrusts -- development of a class nine computer, academic access to present supercomputer centers, and training of research scientists to develop and make effective use of vector codes. NSF also has an advanced computational initiative which has established new supercomputer centers and an academic computing network known as NSFnet, and has provided some local equipment and facilities. Availability of 20% of NCAR's new CRAY XMP is especially important to oceanographers. This CRAY will be linked by satellite network to Miami, Oregon State, WHOI, and other institutions.

Now that we have these badly needed facilities, development of a program to train scientists in numerical ocean modeling seems prudent, especially in light of future modeling and data assimilation requirements. We propose to establish a five-year program in Numerical Ocean Modeling for postdoctoral scientists with training in Applied Mathematics, Computer Science, and Ocean Sciences. These postdoctoral investigators would be resident at academic institutions. Funding for the program would provide salary support, local computing and communications, and travel for ten investigators. Funding needed is \$1M per year beginning in FY 1989.

2. Current Meters. Key elements in advancing our understanding of ocean flow during the past 20 years have been the current meter and the intermediate mooring. Aging, obsolete equipment (some current meters were purchased 15 years ago) must be replaced with new equipment. The level of funding available to the program has not allowed maintenance of current meter and acoustic release inventories. At least \$.7M annually over the next two years is required to purchase new equipment and to return these inventories to a level of sufficiency for the science currently supported.

3. Acoustic (Pop-up, SOFAR, and RAFOS) Floats. Autonomous listening stations (ALS) and acoustically-tracked, neutrally buoyant (SOFAR) floats have recently been improved both mechanically and electronically and redesigned to take advantage of microprocessor technology. Present scientific projects in the North and Tropical Atlantic would benefit greatly from additional SOFAR floats (40) and listening stations (5) at a total cost of \$.7M. We would like to acquire a suite of five pop-up floats for future Gulf Stream or Arabian Sea studies and to expand the RAFOS float capability for related studies at a cost of \$.7M.

4. CTD Group Support. In the past, two CTD groups have been available to meet large project needs; both groups have recently become marginal in their capabilities due to a variety of problems (equipment failures and losses, relocation, management problems, and decreased funding for field work). We think that it is important to reestablish both groups with an up-to-date data processing facility (\$.1M), new at-sea and in situ sampling equipment (\$.2M), and base salary support for a few high quality technicians/engineers (\$.3M) starting in FY 1989. Salary support should continue for an additional four years.

III. Physical Oceanographic Components of the Global Program

There are several program areas where significant advances could be realized.

1. Interannual Variability of the Tropical Oceans and Global Atmosphere (TOGA).

The TOGA program is one of two major ocean climate projects formulated internationally as part of the World Climate Research Program. TOGA began in January 1985 and will last for ten years. Project objectives are:

- (1) to determine to what extent the time dependent behavior of the tropical ocean/global atmosphere system is predictable on time scales of months to years and to understand the mechanism of this behavior; and
- (2) to study the feasibility of modeling the coupled ocean-atmosphere system for the purpose of predicting its variations on time scales of months to years.

As presently formulated, there are three major oceanographic thrusts to TOGA. They include an oceanographic monitoring program to provide a description of month-to-month variability of the temperature, circulation, and pressure fields of the tropical ocean; an air-sea flux measurement program to provide a description of month-to-month variations of fluxes of momentum, heat, and moisture across the air-sea interface; and development of tropical ocean circulation models and associated techniques for data assimilation.

As part of the core programs, we expect that about \$4M will be devoted to tropical oceanography/TOGA on a continuing basis. We consider that participation by the academic ocean sciences community in TOGA activities sponsored by NSF should increase to about three times this level by FY 1992. About half a ship-year would be needed to support this additional activity. We note that Atmospheric Science will sponsor a similar initiative for meteorological studies, and that the Foundation is likely to have special responsibilities for Indian Ocean/TOGA studies.

As part of TOGA, an El Niño rapid response study has been developed. Its purpose is to obtain additional information on atmospheric and oceanographic (physical, chemical, and biological) changes which occur during El Niño. This would be accomplished by redirecting some resources to the Eastern Pacific, but additional funding will also be required in the amount of \$1M per year for three years for collection, analysis, and interpretation of oceanographic data, and one ship-year on an *Oceanus*-class vessel.

2. World Ocean Circulation Experiment (WOCE). WOCE is the second major ocean experiment planned as part of the World Climate Research Program. Many important problems of climate, ocean chemistry, and biology could be solved given the ability to characterize and model the general circulation of the ocean. However, the ocean is a chaotic fluid with temporal and spatial variability on all scales; the lack of observations needed to define important time and space scales for surface forcing and dynamical response constitutes the main reason for our present inability to characterize and understand the general circulation of the ocean.

Recent technical developments should significantly enhance the observational data base available to oceanographers studying general circulation. These include: satellite scatterometry, satellite altimetry, neutrally buoyant and surface floats which can be tracked over great distances, measurements of air-sea fluxes, chemical tracer measurements, acoustic tomography, and eddy-resolving numerical models which can be adapted to operate with basin and global scale data sets in assimilation modes analogous to those used in meteorology.

Because of these new tools, the National Academy of Sciences held a work shop to look into possibilities of developing a program of global observations toward understanding the general circulation of the oceans. The consensus of this workshop was that WOCE was feasible, worthwhile, and timely. Participants agreed that the overall goal of U.S. contributions to WOCE should be *to understand the general circulation of the global ocean well enough to be able to predict ocean response and feedback to long-term changes in the atmosphere.*

Specific objectives to meet this goal are:

- (1) To complete a basic description of the present physical state of the ocean;
- (2) To improve the description of the atmospheric boundary conditions on the global ocean and to establish their uncertainties;
- (3) To describe the upper boundary layer of the ocean adequately for quantitative estimates of water mass transformation;
- (4) To determine the role of interbasin exchanges in the global ocean circulation;
- (5) To determine the role of ocean heat transport and storage in the heat budget of the earth;
- (6) To determine seasonal and interannual oceanic variability on a global scale and to estimate its consequences.

Major hardware costs for WOCE are associated with satellite missions (NROSS, TOPEX, Ocean Color, and GRM) proposed by NASA. We must have at the same time in situ field measurements both at the surface to calibrate satellite data and deeper in the ocean to measure properties and dynamics of the underlying water column. Numerical model development must be closely coupled to these efforts. About 20% of the core program's base budget (\$4M) would be devoted to WOCE activities without additional funding increments.

Additional activities for which funding is required include instrumentation development and acquisition, development of improved data/supercomputer communication links, establishment and operation of data analysis centers, a global hydrographic and tracer survey, an accelerator mass spectrometer (described in the chemical oceanography plan and budgeted under facilities in the Global Ocean Studies section), increased tomography and float capability/activity, process-oriented experiments, and ocean model development. These activities require an additional \$12M in FY 1989 above base funds, increase to \$20M above base funds in FY 1990 and \$30M in the 1990's. This includes WOCE and related activities which are expected to require a total of about 12 ship-years of support during the FY 1989-1996 period; an additional \$2M will be required to upgrade CTD winch capabilities on these ships during WOCE.

The National Science Foundation has been identified as the lead agency for WOCE studies.

3. Coastal Ocean Dynamics and Fluxes. Important studies for this program include circulation, mixing, and particle dispersion in coastal and estuarine waters and large lakes. Base funding for these activities should be adequate for continuation of the present level of effort, e.g., an occasional CODE-type experiment. However, this base funding seems inadequate to support anticipated growth in coastal studies, including addition of physical oceanography faculty at "marine biological" laboratories and at coastal academic institutions which presently employ no physical oceanographers. Faculty members at these primarily state-supported institutions have access to state funding and facilities and can thus carry out some effective studies in local waters with rather modest supplemental funding from the Foundation. Budgeting for this growth fits with NSF infrastructure and undergraduate institution initiatives. \$.5M per year would support five to ten such projects each year.

A second area of projected growth is in multidisciplinary experiments to study the chemical, biological and geological fluxes along and across the continental shelf and slope. The Coastal Ocean Dynamics Experiment (CODE) and Organization of Persistent Upwelling Systems (OPUS) programs have recently discovered a number of new mechanisms for these fluxes, e.g., intense squirts and jets, which can advect shelf water and material hundreds of kilometers offshore into deep water, and energetic oceanic mesoscale eddies, which can directly influence shelf circulation. These phenomena occur on a variety of scales, and these and other recent observations suggest that the flow fields controlling property fluxes over the shelf and slope are much more turbulent than previously imagined. The further definition and understanding of these phenomena needed for studies in other ocean disciplines will require a substantial investment of physical oceanography resources. Support of one such field experiment per year would cost \$2.5M.

Finally, recent theoretical and observational work is beginning to provide the critical intellectual framework needed for more advanced numerical modeling of coastal phenomena. The dynamical roles of bottom friction, stratification, wind and tidal mixing, and coastal topography in wind and buoyancy-forced motions are now better understood and allow construction of more realistic process and regional numerical models. Growth in this area will depend critically on the Foundation, in terms of both encouraging work from a wider group of investigators and providing adequate computational resources, especially access to NCAR. Support for this growth has been budgeted above.

4. Aircraft Capability. Use of scientific aircraft for remote sensing of sea surface and air/sea fluxes has become increasingly important in recent years. Aircraft measurements in conjunction with coastal oceanography experiments are now common for production of maps of wind stress, sea surface temperature, and subsurface temperature (using expendable bathythermographs). Development of geodetic receivers and laser altimeters has increased the utility of these aircraft measurements, as has development of aircraft-mounted passive and active radiometers and radars. In the future, aircraft surveys of dynamic features will be possible, resulting in truly synoptic data at meso- to large scales, and WOCE and TOGA will require extensive measurements of air/sea fluxes, in part to improve our understanding and parameterization of these processes.

To date, NCAR has been able to meet our needs for coastal aircraft measurements, but due to increased atmospheric and oceanographic demands, a second aircraft should be acquired soon. We anticipate that this aircraft would be used half-time for coastal oceanography measurements, and so suggest that \$1.5M dollars be budgeted for acquisition of this aircraft (the Atmospheric Sciences Division (ATM) of NSF would also need to budget \$1.5M). Beginning in FY 1990, \$.5M should be budgeted for ocean sciences activities using this aircraft. Operational costs for the aircraft would be budgeted by ATM, much as the Ocean Sciences Division budgets ship costs.

Ocean sciences will require, in the WOCE time frame, a dedicated aircraft with greater endurance and more capability such as a P2 or P3. We suggest acquisition of such an aircraft in FY 1990, which should be possible at minimal cost (such aircraft are available for use as DOD surplus), and \$.5M for updating avionics and electronic equipment. The aircraft should be budgeted to operate at \$3M per year beginning in FY 1992. If this aircraft is not available, additional ship time would need to be budgeted for WOCE.

It is noted that these aircraft will be especially useful for biological work, as much regional ocean color work will need to be done for productivity studies.

5. Support for an Ocean Modeling Facility. The emergence of geophysical fluid dynamics as a separate theoretical discipline and the success of atmospheric scientists in predicting and modeling the atmosphere are having a profound effect on the interplay of theory and observation in physical oceanography. There is a greatly expanding need for numerical experiments not only for interpretation of data, but also for justification of observational efforts. In looking to meet these needs, we funded 20% of the acquisition costs of an advanced vector computer and wide-band communications equipment at the NCAR in FY 1985, and we should also establish an Ocean Modeling Facility to utilize this capability.

The purpose of this initiative is to provide base funding for a core group at a central location to aid the ocean sciences community in making effective use of the facility, e.g., building community models, specialized routines, and hardware. This would provide for scientific and senior staff communications costs for the academic community, space rental and maintenance, and hardware costs. The total cost of this support is \$1.1 M per year (beginning in FY 1989) and should be budgeted indefinitely.

6. Indo-U.S. Monsoon Research Program. As part of the Indo-U.S. Science and Technology Initiative, a program to study long-term variability of the monsoon includes a study of the effect of ocean-atmosphere interactions. A bilateral workshop was held in Bangalore, India, for discussions of modeling, data analysis, future field experiments and data requirements. U.S. modeling and data analysis work required \$0.6M in FY 1987. Tentative plans call for continuation of modeling work and initiation of field experiments toward understanding the regional ocean atmosphere coupling problems.

These programs would require an additional \$1.8M per year for scientific studies and \$.7M per year for ship time by FY 1990 from the U.S. The direction of research beyond 1990 should be coordinated with the TOGA program.

IV. Funding Requirements

A summary budget for the physical oceanography core program, areas of critical need, and major initiatives can be found in Table A of Section IV.

B. Chemical Oceanography Program Long-Range Planning

I. The Core Program

The Chemical Oceanography Program is directed toward providing an understanding of how oceans, estuaries, and large lakes function as chemical systems and how they respond when perturbed by nature or man. These efforts address such global problems as sea-air exchanges and particulate fluxes. They provide the scientific underpinning for dealing effectively with socioeconomic problems including pollution, deep-sea mining, agriculture, and open-ocean waste disposal and with other scientific problems requiring marine chemical input such as sediment diagenesis, climate, ocean circulation, and biological productivity. Broad goals of these activities are:

- (1) To describe quantitatively the types of reactions (i.e., processes and mechanisms) that occur between the various phases and chemical species existing in the marine environment; and
- (2) To determine routes and rates of supply to and removal of substances from the ocean, and the alterations which occur during transit.

For descriptive purposes, the program is divided into five components. These are:

- (1) Seawater chemical equilibria and physicochemical properties;
- (2) Material transfers and transformations at the land/sea boundary;
- (3) Fluxes of material to, transport through, and alteration in ocean basins;
- (4) The role and influence of biochemical processes on the chemical nature of seawater; and
- (5) Development and use of chemical tracers to study large-scale temporal processes in the oceans.

Because boundaries between these components are somewhat diffuse, their interrelations are discussed below. Budgetary history and projections in the core program are shown in the tables.

1. Seawater Chemical Equilibria and Physicochemical Properties. This component includes studies on equilibria of chemical species and compounds in seawater and their availability for reacting with other chemical phases in the marine environment.

Through efforts of a diverse group of physical chemists and physical oceanographers, a universal equation of state for seawater has been recently adopted, and new insights on dissociation constants of major seawater equilibria (e.g., the carbonate system) have been developed. Future research will be directed towards further developing speciation and ionic interaction models in seawater, including microbially mediated reactions and thermodynamic and kinetic investigations on marine photochemical reactions. The relative level of effort, however, is projected to decrease slightly to allow other areas of the program to increase.

2. Material Transfers and Transformations at the Land/Sea Boundary. Research at this interface is focused on displacement of heterogeneous equilibria and on chemical fluxes in the upper sediment and porous crust. Major scientific breakthroughs have occurred in this area in recent years as a result of joint efforts with Biological Oceanography and Marine Geology and Geophysics. An example is the discovery of and follow-on work concerning hydrothermal vents.

Activity has increased in the recent past, and with new vents being found (e.g., hydrothermal methane plumes in the North Fiji Basin in February 1986), this trend is likely to continue. Moreover, bottom landers and other similar instrument packages will provide a technology whereby heretofore impossible studies on chemical processes and mechanisms at the ocean bottom boundary will begin. Core resources required for studies in this component will increase somewhat in the immediate future, including associated ship and submersible time and construction of samplers and analytical instrumentation for deployment from ships or from *Alvin*.

3. Fluxes of Material to, Transport Through, and Alteration in Ocean Basins. This component is aimed at understanding and measuring fluxes in ocean basins, including sources and input from the troposphere to the ocean surface, lateral injection of material from the coastal boundary, and transport through the water column to underlying sediment. The state of the art for following particles through the atmosphere to the ocean surface and for quantifying fluxes of particulate material by collection and analysis of material in sediment traps has increased notably over the past several years.

Major programs have contributed to this understanding during the last decade (e.g., Sea-Air Exchange Program, Vertical Exchange Program, and ADIOS). Several other National Science Foundation Programs also have contributed to support of this research, either through joint support of individual awards or of major thrusts in atmospheric, biological, geological, and physical sciences.

Progress has been significant, but for the most part it has remained within specific disciplinary areas. The coupling of rates and characteristics of material passing between the troposphere and the ocean must now be considered. Some material falling through the ocean depends upon how particles are packaged by marine organisms and the stability of these biogenic containers as they pass through domains of varying temperature, oxygen content, and acidity. Metals capable of being adsorbed on particles, for example, can be scavenged from and then released to the water several times during their descent.

These same particles could have originated from desert regions and been carried aerially through tortuous paths in the lower atmosphere before beginning their equilibration with seawater. Investigators are now relating rates of input to the surface with fluxes carrying material to the bottom. Clearly, significant complementary biological and physical oceanographic information is required to understand the entire process fully.

4. The Role and Influence of Biochemical Processes on the Chemical Nature of Seawater. The objective of this component is to understand the chemical and biological mechanisms that together control the nature of the marine environment. Development of this major component of the Chemical Oceanography Program arose from advances in marine organic chemistry and in microbiology, advances based on constantly developing instrumental capabilities, most notably temperature-programmed capillary column gas chromatography-mass spectrometry, flow cytometry, image analysis, and high-performance liquid chromatography. New techniques and instrumentation continue to open up opportunities for study of organic matter distribution and reaction mechanisms in seawater and sediments.

Isotopic tracers and organic source markers are new techniques for advancing marine organic chemistry. It is now possible to determine carbon isotopic composition of functional groups on individual organic compounds. This allows more specific information to be gained regarding biosynthesis and sources of individual compounds as well as mechanisms of their transformation reactions over time. Close collaboration with the Biological Oceanography Program will continue and probably increase in these areas.

5. Development and Use of Chemical Tracers to Study Large-Scale Temporal Processes in the Ocean. This area of research has progressed rapidly during the last five years due principally to increased precision in analyzing radio isotopes in seawater and development of sampling and analytical techniques for measurement of new tracers that have unique source functions (e.g., freons). Because geochemical and physical sampling strategies are often incompatible, plans are now being devised for multiship coverage to accommodate infrequent large-volume samples and a denser sampling grid for smaller samples. The latter accommodates most physical oceanographic sampling and measurement schemes. New tracers include pairs of constituents requiring both small- and large-volume samples. For example, freon and krypton complement each other as conservative tracers, with one of them, krypton, decaying predictably so that the age of water parcels can be obtained.

Activities in this area will proceed into the southern hemisphere incorporating higher precision in analytical methods and more efficient sampling strategies that will combine large- and small-volume samplers. Results from the South Atlantic will complement data already collected for the North and Tropical Atlantic. This study will also complement efforts of other projects such as SEAREX, VERTEX, Warm Core Rings, and future efforts concerned with biogeochemical cycles/balances and ocean fluxes. International cooperation is expected to continue along the pattern set during Geochemical Ocean Sections Study (GEOSECS) activities. However, the ability of foreign laboratories to conduct extensive large-volume sample processing, as for GEOSECS in the 1970's, is now paralleled by facilities supported in the United States (e.g., for ^{85}Kr , ^{39}Ar , ^{228}Ra , ^{90}Sr , ^{137}Cs and ^{14}C).

Foreign ship-of-opportunity programs are essential for the tracer coverage required, but they cannot substitute for well-designed and well-managed sampling programs using large dedicated research vessels of the UNOLS fleet. Close collaboration with the Physical Oceanography Program will be maintained to coordinate transient tracer studies with modeling efforts conducted in WOCE. Tracer information is extremely useful to physical oceanographers to provide additional constraints on circulation models.

II. Critical Needs of the Core Program

Besides the critical needs common to all the programs described in Section II.A, certain elements of the core Chemical Oceanography Program, as well as the Open Ocean Fluxes program, need special support in order to exploit current developments in the field. This is particularly true of accelerator mass spectrometry, which will also be vital to the WOCE program and the Marine Geology and Geophysics Program.

Accelerator Mass Spectrometry Facilities. Recent achievements in accelerator mass spectrometry (AMS) have convinced a wide spectrum of environmental scientists to assign an extremely high priority to developing a dedicated Ocean Sciences AMS facility in the U.S. The AMS technique combines conventional methods of mass spectrometry (ionization and mass discrimination by magnetic and electrostatic fields) with acceleration through high potentials of 1-15 MV to achieve spectacular increases in analytical sensitivity. Because AMS lowers previously attainable detection limits by several orders of magnitude, it opens up a wide range of very significant scientific opportunities and brings a previously difficult span of earth history within reach of quantitative interpretation.

The achievements referred to above include use of ^{14}C to reconstruct ocean ventilation rates, direct confirmation of the plate tectonic cycle of subduction-melting-volcanic eruption with ^{10}Be tracer, and the first-ever determination of the rate of groundwater flow through a major aquifer using ^{36}Cl dating. Use of AMS has also made major contributions to studies of such diverse problems as ocean circulation, soil and rock erosion rates, dating ice cores and cave deposits, climate variations, origins of meteorites, atmospheric chemistry, waste containment in geologic repositories, hydrothermal and ore-forming fluid circulation patterns, and direct dating of petroleum fluids.

The wide potential of AMS makes it imperative that we begin planning immediately to develop an AMS capability in the U.S. One possibility is for an AMS facility to be developed around a new Tandatron accelerator or its equivalent. This facility would respond to the rapidly growing needs of ocean scientists for precise ^{14}C analysis. Establishment costs for this facility are estimated at \$5M, including capital construction, with \$1M operating funds for FY 1989 and beyond. These funds are incorporated in the facilities budget of the Global Ocean Studies because of the wide utility of this facility.

III. Chemical Components of the Global Program

Global initiatives will involve the Chemical Program in a variety of areas, particularly in the context of global ocean flux studies, which are sub-divided here into open ocean and coastal components.

1. Open Ocean Fluxes. A major goal for ocean sciences over the next decade will be to determine the biogeochemical cycles and budgets in ocean basins over long time scales. The physical dynamics (steady state and first order variability) essential to meeting this goal will be obtained through research programs such as WOCE and the continuation of tracer studies. A determination of the character and primary productivity of the sea surface will also be available globally and synoptically from satellite and airborne sensors. Finally, the very important lateral flux from the coastal boundary zone will be available from studies conducted in that region.

With these dynamic and boundary conditions, a most exciting opportunity exists to link them with extensive in situ observations of fluxes of soluble and particulate phases and transformations between them. New tools and techniques (e.g., sediment traps, large-volume samplers, experimental benthic chambers, and numerical modeling) will be developed and used extensively in conjunction with physical and satellite observation programs over the next decade. This program will provide an understanding of the factors which control long-term chemical/biological dynamics at the ocean basin or global scale.

Of particular relevance here is the application of emerging methodology employing AMS for measuring ^{14}C , ^{10}Be , ^{129}I , and ^{26}Al concentrations in seawater. Additionally, significant effort will be required to assure that the necessary infrastructure is in place to guarantee that the volumes of data produced from satellites and aircraft can be handled.

The specific objectives of this initiative are: (1) to define the rate of production of organic matter (i.e., organic tissue, opal, calcite, and many of the specific chemical and biological components of these phases) as a function of geographic location and time; (2) to define the flux of organic matter from the photic zone into the ocean interior as a function of location and time; (3) to define the transfer rates (by respiration, dissolution, and sorption) between phases as a function of time and location within the water column; and (4) to define the flux between the ocean interior and the seafloor. Several major aspects of the ocean sciences will benefit from having results of this research applied to specific regions.

A knowledge of rates of photosynthesis and respiration as a function of space and time in the sea is fundamental to any understanding of the ecology of marine organisms. A knowledge of production and dissolution patterns of opal and calcite hard parts is fundamental to reading the record of paleoenvironments preserved in marine sediments. Finally, knowledge of the pattern of nutrient transport to the ocean's surface and of the pattern of nutrient regeneration in the sea's interior will provide powerful constraints on models of water flow through the sea.

To accomplish a synoptic study of this scale and match fluxes to and through the water column, a seven-year program costing between \$5M and \$8M per year is required, with an additional \$6M required in FY 1988 and FY 1989 for establishing a dedicated AMS facility for the Ocean Sciences.

2. Coastal Ocean Fluxes. The objective of this subinitiative is to determine the extent and nature of material being injected into the open ocean across the coastal boundary. The results of this research will be augmented by studies of the Land/Sea Interface and Continental Margins and will serve as the input function for models developed to describe global open ocean flux studies (GOFS).

Mass balances of both meso and global space scales are necessary in determining whether the influx of material to the ocean is greater than its removal. The approach has been applied with regard to some metals in seawater, and results indicate that a substantial increase in the oceanic inventory of certain metals has occurred as a result of human activity. However, these efforts have been severely limited by a lack of comprehensive models. It is likely that global models will be generated using regional models; therefore, the geographic setting must be predetermined.

Two natural modes of input of terrestrial and man-mobilized material into the ocean are atmospheric fallout and river discharge. The SEAREX Program has increased our understanding of the former. Riverine transport studies are more complex since influxes do not go directly into offshore waters of regional seas or global oceans, but first pass through estuaries and other nearshore environments. River-carried material therefore does not represent actual riverine fluxes to the ocean proper. Other important modes for introduction of material, especially for wholly artificial substances, are through direct discharge from land via pipelines and through dumping by ships at sea.

In the case of naturally occurring contaminants, such as metals, it is also important to quantify natural influxes. These include emissions from tectonic spreading centers and hydrothermal vents and influxes from runoff other than rivers, such as glaciers. These sources need to be placed in perspective with regard to the role that rivers play. The net input to the open ocean is that material which survives chemical and biological removal and reinjection as it traverses the estuarine environment and the coastal-open ocean boundary. Physical characteristics of these areas also play an important role in transport.

The chemical components of this estuarine transport study would require from \$2 to \$4M of new support per year over a five-year period.

3. Ocean Lithosphere and Ridge Crest Processes (Chemical Component). An initiative in Geological Oceanography describes the geological, chemical, and biological aspects of understanding how lithosphere and ridge crest processes work. The support needed for studies of sulfide mineralization, vent water chemistry and seawater leaching of porous crust will be \$2M per year.

4. Recruitment Mechanisms (Chemical Component). This initiative in Biological Oceanography requires studies of chemical input to assess food chain shifts resulting from dissolved material in the water column. Between \$1M and \$2M per year will be required to perform these chemical studies of recruitment.

5. Tracer Studies in WOCE. A critical step in any effort to predict the role of the ocean as a sink (e.g., for fossil fuel CO₂) and its ability to transport chemicals both vertically and horizontally is creation of models of ocean circulation and mixing. Present models are limited and a major obstacle to their future development is a lack of data with which to constrain them. Chemical tracers offer the best means of providing these constraints. As a result, one of the major objectives of TTO, initiated in 1978 jointly with the Department of Energy, is to obtain a fully three-dimensional picture of tracer distributions throughout the world ocean.

Large field-intensive oceanographic research, such as study of tracers, depends upon well-maintained and efficiently operated ship support facilities comprised of sampling equipment, in-situ measurement devices, analytical instruments, computers, and staff to operate these facilities to provide requisite data handling and management capabilities. With the advent of large-scale oceanographic field studies lasting several months, permanent technical staff are needed to handle support activities efficiently.

In the past there have been two groups available to meet project needs. Both groups have recently become marginal in their capabilities due to equipment failures and losses, relocations, management problems, and decreased funding for field work. For the Global Program we must reestablish both groups, with up-to-date processing facilities, with new or refurbished sampling equipment, and with continuing support for a few excellent engineers and technicians.

6. The Land/Sea Interface: This is an expansion of the core program on Material Transfers and Transformations at the Land/Sea Boundary. It is being planned jointly by the Ocean Sciences and the Biotic Systems and Resources Divisions. The objectives are defined under the Global Program and in the Biological Oceanography program description.

V. Recommended Funding

The recommended future funding for the Chemical Oceanography Program overall, including the core program, enhancements and major new initiatives, is provided in Table B of Section IV.

C. Biological Oceanography Program Long-Range Planning

I. The Core Program

Biological oceanography is the subdiscipline of oceanography concerned with the study and prediction of the interrelationships of marine biota with one another and with the physical, chemical, and geological features of the ocean and atmosphere. A central focus is to understand ecosystems on both regional (e.g., estuarine, coastal embayment, central gyre, ocean basin) and, ultimately, global scales.

Biological Oceanography has come of age over the past 15 years with increased participation in major interdisciplinary programs such as Coastal Upwelling Ecosystems, Gulf Stream Rings, and Hydrothermal Vents. Biological oceanographers have taken advantage of steadily developing sampling technology towards real-time, in situ measurements (e.g., fluorometry, respirometry, ocean color sensors) compatible with those of chemistry and physics. They have also recognized the significance of new and complex communities (e.g., those comprising the microbial loop, the gelatinous midwater communities, and hydrothermal vent organisms). Biological Oceanography is now poised, with its sister disciplines, to expand its vision to interdisciplinary global processes. These include interconnections, not only between the coastal and open ocean, the ocean and atmosphere, and the ocean surface and sediments, but also between terrestrial and freshwater environments and the coastal ocean.

The core program in Biological Oceanography may be subdivided into:

- (1) primary production processes (benthic and water column),
- (2) microbial loop processes,
- (3) higher trophic levels,
- (4) specialized environments (deep ocean floor including vents, coral reefs, oxygen minima, etc.), and
- (5) large marine ecosystems and their control by physical and chemical processes.

These divisions are not mutually exclusive. Programs focused on communities (4) and ecosystems (5) often involve the first three areas.

1. Primary Production Processes. The nature and rate of primary formation of biological material, a central theme of biological oceanography from its earliest days, still holds center stage. Primary production is the basis of all marine food chains and biological production of economic importance, and it plays a central role in the flux of material to the deep ocean and in the control of climate through CO₂ cycling.

The struggle to compute total ocean primary production accurately and to determine the relative significance of component ecosystems continues as more sophisticated tools become available. The subtle complexities of such integrations are being pursued through research on the physiology and biochemistry of photosynthesis and metabolic activities of single cells, the rigorous intercomparison and evaluation of the methodologies of primary production measurement, and the expanding range of primary production processes including photo- and chemosynthetic bacteria, nitrogen fixation and the role of submicron "picoplankton." The concept of new versus recycled production is sharpening definitions of regional potential for secondary productivity (e.g., fish production).

The promise of a renewed capability for large-scale synoptic satellite color sensing is stimulating reexamination of the relative roles of shelf and open ocean waters in marine productivity. It is also, of necessity, stimulating efforts toward quantitative calibration of ocean color in terms of primary production in preparation for the next decade. These core studies are particularly important for global (both coastal and open) ocean flux and recruitment subinitiatives, as well as global productivity.

2. Microbial Loop Processes. As little as two decades ago, marine bacteria and other heterotrophic microorganisms were thought to be rather rare and largely inactive. They are now known to be responsible for up to 50% of the total water column biomass. They can consume up to 50% of the total primary production in some situations and over 80% of water column respiratory activity remains after filtration through a 1-micrometer filter.

Growing knowledge of the vital and active role of microorganisms in marine food chains has vastly complicated the old "simple" diatom-copepod-fish short food chain concept. We now realize that intricate microscale food chains may be responsible for rapid recycling of material in the upper water column and transformation of detrital remains sinking to the ocean floor. Further definition of the role of ocean microbes will provide a major component of ocean flux studies.

3. Higher Trophic Levels. Ecological studies of populations and communities above the microbial level and their behavior and ecological interactions have also added immeasurably to our current understanding of the sophistication of ocean ecosystems. One significant example is the exotic gelatinous zooplankton. Their importance was first determined by scientists using near-surface scuba techniques; submersibles are now being used for studying them at greater depths. In standard texts on marine invertebrates, whole chapters can now be written where formerly groups such as Foraminifera, Radiolaria, salps, ctenophores, and chaetognaths were dismissed in a sentence or two.

Complex predator/prey interactions are being explored in imaginatively designed field studies and in controlled laboratory studies. Sophisticated instrumentation is being developed to analyze swimming behavior in three dimensions, to slow down millisecond-rate activities of the microscopic mouth parts of copepods, and to measure flow velocities over feeding appendages of benthic organisms. The biochemical basis of larval settlement and the competitive overgrowth of clonal encrusting organisms are but two examples of ecological studies needing support for a better understanding of major groups of organisms comprising coastal and oceanic ecosystems. Basic life history and biology studies of individual populations are requisite for understanding the seasonal, interannual, and longer scale regulation of populations and communities, and they are relevant to the recruitment processes and ecosystem dynamics subinitiative.

4. Special Environments. The outstanding examples in this category are the specialized and unique communities living around hydrothermal vents. Scientists continue to be fascinated by the diversity of unusual life styles and unique adaptations of these organisms. As new hyperthermal and isothermal vent environments are discovered, we can expect further insights into basic phenomena involving symbiosis, sulfide metabolism, the nature and pace of evolution, and adaptation to extreme environments. The complex organization and extremely high productivity of the rich, diverse coral reef fauna also demand further study. Other specialized environments that will continue to command interest include localized upwelling regions, sub-surface oxygen minimum zones, and seagrass and kelp forests.

The potential applications to biotechnology of organisms adapted to specialized environments cannot be underestimated.

5. Large Marine Ecosystems. Comprehensive investigations of marine ecosystems through interdisciplinary approaches are an important part of the Biological Oceanography program. The percentage of total awarded dollars for such research has fluctuated between 25 and 40% over the past 5 years. Large interdisciplinary programs were funded through the International Decade for Ocean Exploration (IDOE) in the 1970's and have been administered as OSRS programs since 1981. The IDOE phase-out was followed initially by a decline in dollars spent on multiinvestigator, multiinstitutional awards in biological oceanography. However, increasing numbers of large interdisciplinary programs have been funded since 1981.

Recently concluded large programs in which biological oceanographers had major involvement include Warm Core Rings, Organization of Persistent Upwelling Systems (OPUS), and Planktonic Rate Processes in Oligotrophic Oceans (PRPOOS). Current large programs include the Vertical Exchange Program (VERTEX), SUPER, and Microbial Exchanges and Coupling in Coastal Atlantic Systems (MECCAS) for the water column, and Hydrothermal Vents for the benthos. Future basinwide interdisciplinary studies are projected for the Indian Ocean, where predictable regular monsoonal upwellings cause intense production and extreme oxygen minimum layers, and for higher latitudes, where new production is likely to be a much higher proportion of the total. The phasing in of ocean and coastal flux and recruitment processes studies, described below, will bring greater emphasis on large ecosystems and interdisciplinary research. It is also vital, however, to maintain the core of individual investigator research.

II. Critical Needs of the Core Program

Special funds (see the tables) are necessary to supplement core program funding in all the areas addressed in Section II.B of the Long-Range Plan. Two of these are highlighted below as particularly urgent.

1. Biochemistry, Chemical Ecology, and Marine Biotechnology. There is an immediate need for substantially enlarged research support to accommodate the accelerating numbers of exciting proposals in this burgeoning field. Increasingly, biological oceanographers are employing the techniques of analytical biochemistry to studies of microbial ecology, sediment biogeochemistry, metabolic biochemistry, and chemically-mediated organism interactions, and to their applications in biotechnology.

The application of new analytical and molecular research tools to studies of the evolutionary diversity of marine organisms and their colonization of unique and extreme environments will produce important new discoveries. Enhancement of this work is projected to require \$1.5M in FY 1988 and to increase rapidly beyond this as marine biotechnology grows in importance. Besides the obvious need for research dollars, we also see the need for enhancement of existing centers through acquisition of the expensive new generation of instrumentation to integrate modern molecular biology and genetic technologies into the ocean sciences. We also need to encourage establishment of new centers in the context of existing marine laboratory and oceanography facilities, where seawater systems, culture expertise, and ecological knowledge of the habitats of marine organisms already exist. This program will require a \$10M annual budget within five years.

2. Technology Development. Development, acquisition, and use of new tools for field data acquisition and analysis is a most critical need in biological oceanography. Support for the technical personnel to operate and maintain such complex electronic and mechanical equipment is also vital. A small proportion of the resources of the Oceanographic Centers and Facilities Section is assigned to ongoing technology development for the Ocean Sciences Division as a whole, but it is inadequate to equip Biological Oceanography with a new generation of field observational and data management tools.

Specific prototype research methods that would contribute significantly to advances in Biological Oceanography with enhanced support include (1) multifrequency acoustic sampling for zooplankton and small nekton; (2) in situ optical sampling and image analysis for plankton, microbes and marine snow; (3) flow cytometry and image analysis for identification and sorting of phytoplankton and microbes; (4) satellite data capture and analysis; and (5) optimally designed submersibles for investigation of midwater plankton and benthos. Greatly expanded funding for these and other endeavors will allow biological oceanographers to develop state-of-the art observational capabilities and will insure real-time interaction with physical and chemical oceanographers in future interdisciplinary and large-scale programs.

This enhancement will require at least \$5M per year over the next decade.

III. Biological Oceanography Component of the Global Program

Biological Oceanography contributes major components to the Global Ocean Studies Program, and a minor component to the Ocean Lithosphere Studies Program, the latter in connection with the biological communities associated with Ridge Crest Processes. Planning funds have been assigned starting in 1987.

Within the context of Global Ocean Studies, the biological and chemical components of Global Ocean Flux Studies (GOFS) are furthest advanced, and are scheduled to begin pilot field studies in 1989. The Land/Sea Interface study, a program being jointly planned with the Chemical Oceanography Program and the Division of Biotic Systems and Resources, is scheduled to receive funds for planning beginning in 1988. Recruitment Processes and Ecosystem Dynamics as a subinitiative has been endorsed by the Ocean Studies Board of the National Academy of Sciences, and following further planning workshops it will start in 1989. Coastal Fluxes and Dynamics, a multidisciplinary series of programs, is beginning to be organized and may also be expected to become structurally defined by 1989 in preparation for major field activities in the next decade. The biological component of Global Circulation, Climate, and Productivity is seen in a supporting role for all of the above. The order of presentation below maintains consistency with the other parts of this document and does not reflect an order of priority.

1. Global (Circulation, Climate, and) Productivity. Within the ocean sciences, this program encompasses such well-established efforts as TOGA and WOCE. Within the Biological Oceanography Program, global productivity studies will not be developed as a major focus, but continuing core studies will serve the needs of the coastal and ocean flux studies subinitiatives, as well as those for recruitment processes and the land/sea interface. If these efforts are to succeed, significant supplementary funds must be set aside for the acquisition, groundtruthing, assimilation, and management of the expected data stream from satellite and aircraft sensors and from ships at sea.

Although the coastal zone color scanner is now a memory, there will be a new generation of color sensors, the earliest of which could be spaceborne by late 1990, followed by multispectral instruments capable of resolving up to 100 separate spectral bands. These sensors are likely to be commercialized and hence the cost of their data gathering may have to be borne by NSF in partnership with other agencies for the academic community. In addition, there already exists a wealth of productivity data collected from past programs and stored in a variety of often inaccessible data bases scattered through the literature, both in published and technical report form. Additionally, major cruises of the global ocean programs, including TOGA, WOCE, and GOFS, will generate new productivity data over the next decade.

Funds must be projected now for (1) acquisition of hardware, facilities, and data links for academic institutions; (2) training of graduate and postdoctoral students in remote sensing technology and integration of biology into coupled ocean/atmosphere models requiring super computers; (3) detailed analysis of currently archived data; (4) ground truthing and the development of new algorithms for higher latitudes and the conversion of ocean color to reliable production estimates; (5) the actual cost of new commercial products; and (6) development of data assimilation and management schemes, identification of specific sites for these activities,

and the means of dissemination of global and regional productivity data to feed the requirements of Open Ocean and Coastal Dynamics and Fluxes programs, the Land/sea Interface, and Recruitment Processes. Some of these activities are currently being funded at a minimal level in the core program. By FY 1989 the effort will require at least an additional \$2M, increasing to \$6M by FY 1993.

Global Ocean Flux Studies will require an interdisciplinary effort by chemical, biological, physical, and geological oceanographers. The sediment trap will be one of the major sampling tools, but the diversity of biological projects needed will require major use of traditional and new sampling technologies. From a biologist's perspective, the most effective flux program design would incorporate onshore-offshore sampling to estimate influences of terrestrial sources, basin boundaries, and advective processes on both the vertical and horizontal movement of materials. For convenience, the program can be sub-divided into open ocean and coastal components.

2. Open Ocean Fluxes A major research effort is required to examine the flux of biogenic particles from the sea surface to the benthos and the mechanisms by which materials are transported, transformed, and cycled. Rates of primary production and seasonal succession of phytoplankton species, loss and regeneration rates of nutrients, dynamics of plankton communities, and energetics at the organism, population, and community level all must be studied to understand particulate flux.

The fate of particulates reaching the seabed, the effect of turbulence on benthic organisms, the pathways by which benthic communities utilize, transform, and regenerate materials, and the role of nekton in both lateral and vertical transport of materials must be considered. Because flux of materials varies between ocean basins and with the seasons and climatic conditions, a successful program will require broad coverage of major marine ecosystems and multiyear commitments to measure intra- and interannual variability.

Planning and long-lead time activities for a community effort designated Global Ocean Flux Studies began in 1986 with the joint assistance of NASA and NSF. Pilot ocean basin observational programs will be mounted before the end of this decade. The biological oceanography component of this program will require \$2M by FY 1989 increasing to \$10M by FY 1992 when full scale global field programs should be in place. This will help biological oceanographers to phase into a major interdisciplinary flux program and allow development of instrumentation as well as training of technical personnel critical to the initiative's success. These figures include the funds required to help support ship and facility operation and the establishment of an Ocean Sciences Accelerator Mass Spectrometry Center essential to both the GOFS and WOCE programs.

3. Coastal Ocean Dynamics and Fluxes. The new in situ and satellite imagery tools provided oceanographers with the first vivid realization of the complex dynamics of the micro- and mesoscale physical structure and its inevitable consequences for sediment transport, geochemistry, and population recruitment processes. This dynamic mosaic of currents, upwelling, eddies, and jets has been clearly seen to influence equally complex patterns of ocean surface color, itself an index of biomass and productivity as revealed by the coastal zone color scanner.

From a biological perspective, the coastal ocean has two important characteristics distinguishing it from the open ocean: (1) very high rates of biological productivity based on upwelling and the influx of nutrients from land, and (2) dynamic interactions at the seabed interface. High variability in space and time characterize processes related to these phenomena. This has traditionally confounded interpretation and understanding, but it is increasingly apparent that these processes, governed by ocean physics, are very much less stochastic than formerly thought. This apparent noise in coastal biological patterns and processes is made up of important signals which several programs are being designed to unravel.

One of these is MECCAS, already in its first field phase. It is designed to follow the Chesapeake Bay estuary plume onto the continental shelf and to determine the biological transformations taking place along its path and its effects on the productivity of the adjacent region. In a second physical/meteorological program, biologists are involved in assessing the effects of the passage of coastal winter storms on fish spawning and larval survival. There are programs in advanced planning stages designed to investigate the biological significance of sediment resuspension caused by storms, waves, and currents off the coast of California. Many organisms important to productivity cycles, from dinoflagellates to copepods, are now known to produce resting spores or eggs which accumulate in sediments.

Transient physical phenomena may be responsible for the bulk of biological production in some regions of the coastal ocean. Another planned program takes as its premise the global biological significance of western boundary currents, which are an order of magnitude less intense than eastern boundary upwellings but often occur over much longer coastlines and are often sustained over large parts of the year. The potential for nutrient enrichment of coastal regions and the fate of subsequent particulates produced are currently a matter for speculation, but it is certain that large amounts of biogenic carbon are fluxed across the ocean margin into the deep ocean basins.

Funds to support biological aspects of a coastal flux program will need to begin by FY 1989 and sharply increase to \$6M by FY 1994.

4. Global Ocean Ecosystems Dynamics and Recruitment. Animal populations frequently vary in abundance year to year by orders of magnitude, usually due to variable survival of larval or juvenile stages. Climate, physical processes, variability in primary production or zooplankton production, and variability in predation have been hypothesized to regulate such large changes, which often have huge economic impacts. This NSF initiative, together with efforts planned by the International Council for the Exploration of the Sea (ICES), UNESCO, and FAO (and their member states, including France and the U.K.) could provide new solutions to understanding recruitment variability and ecosystems dynamics in temperate and tropical seas.

A central question concerns the mechanisms by which relatively small (three- to-fourfold) variability in annual primary production within an ecosystem is magnified to express ten- to hundredfold variability in fish or benthos recruitment. Differences in recruitment mechanisms in high and low latitude systems need to be considered as do probable differences associated with the dominant type of primary producer at the food chain base. Predicting recruitment and shifts

in abundances of commercially important fishes (e.g., sardine/anchovy), based on ocean and climate parameters, would have great economic and social benefits for fisheries harvests and management. It is important to know the sequence and temporal-spatial scales of events that lead to failures or successes in recruitment in order to make predictions about the long-term changes of population structure.

A Recruitment Processes and Ecosystems Dynamics program will require funding for studies in both coastal and oceanic ecosystems and the use of mesocosms for controlled experiments to examine factors that influence recruitment. Initial research will focus on larval stages of fishes and benthic invertebrates. As in other biological oceanography initiatives, strong input from physical oceanographers will be required to allow collaborative investigation of factors that aggregate or disperse larvae, their predators, and their prey. The role of predation and its effects on the recruitment process will be a particularly important topic for investigation.

As in the other subinitiatives, there is a critical requirement to develop new samplers, instrumentation, and analytical techniques, and to train technical personnel. The control of ecosystem structure through recruitment processes in the coastal and continental shelf and slope environments is particularly important, because this is where the bulk of the harvestable biomass resides. Among the obviously important controls on recruitment processes are the physical, chemical, and sediment transport considerations embodied in the Coastal Ocean Dynamics and Fluxes subinitiative.

Core program funds up to \$4M are already being spent in this area. We should expect to expend at least \$2-4.5M per year in the FY 1989-90 time frame increasing to \$10.5M per year by FY 1993, in order to make really significant contributions to planned international programs on recruitment problems and ocean ecosystems dynamics.

5. The Land/Sea Interface. Traditionally, terrestrial, freshwater, and ocean research have been separated both at academic institutions and at federal agencies. Nevertheless, their geographic interconnection, especially in large terrestrial drainage systems and their estuaries, offers a unique opportunity for NSF to provide leadership and catalyze integration at a critical juncture. These transitional ecosystems contribute enormously to the livelihood and well-being of the global human population, which itself endangers their health.

Environments at the land/sea interface continually change because of natural variability of climate and runoff and because of their sensitivity to small changes in sea level and to storms. Recently, the change has been accelerated as these environments have been subjected to human-caused increases in the amounts of freshwater, sediments, and nonnatural (and often toxic) materials moving from the land to the oceans. Populations of organisms have also been greatly changed in recent years because of habitat alterations and intense harvesting. In the next century, the predicted greenhouse effect may cause global climate changes resulting in changes in river runoff and temperature.

We need to begin to plan a long term research program to monitor and document changes and to specify the studies that will enable us to predict the effects of these changes on aquatic ecosystems at the land/sea interface. We expect that \$1M increasing to \$6M will need to be allocated to OCE efforts between FY 1989-93 (with an equal amount being provided by BSR) and maintained at that level through 1996.

6. Ridge Crest Processes. This program includes a significant biological component. To understand fully the origin and evolution of biological communities, a long-term integrated biological program should be coupled to geochemical flux studies and directed toward the unique properties of vent organisms with emphasis on chemolithotrophic microbes, symbiont-host relations, bioenergetics, and physiological adaptations.

To define community structure, life history strategies, and evolution of biological communities, a number of important questions must be asked. These include: What are the most important factors sustaining vent biological communities - nutrients, heat, symbiosis? How do vent communities colonize new areas? How do communities evolve? What are the mechanisms for adaptation to the unique chemistry, high temperature, and high pressure? What are the productivity and the physiology of vent organisms?

7. Funding Requirements

Funding requirements for the Program are detailed in Table C of Section IV.

D. Marine Geology and Geophysics Program Long-Range Planning

I. Core Program

Major changes in marine geoscience research have occurred in the fifteen years since acceptance of plate tectonics theory. Reconnaissance studies of sediment distribution and composition, crustal age and chemistry, and ocean basin structure and history have set the stage for detailed examination of (1) the "how" and "why" of plate tectonic processes; (2) the mechanisms of global climate and ocean circulation changes as recorded in deep sea sediments; (3) the temporal and spatial scales of seafloor formation and their control on crustal heterogeneity; (4) seawater chemistry and formation of mineral deposits; (5) the stretching and subsidence of rifted continental margins; and (6) the mechanisms for crustal accretion and erosion in deep sea trenches.

New instruments allow the geologist to image the seafloor in real time on spatial scales of meters to kilometers (swath mapping, side-scan sonars, and cameras) and permit the geophysicist to probe the deepest sedimentary and igneous layers beneath the margins and ocean basins (large-aperture seismic arrays, broadband digital reflection profiling systems, satellite geodesy, and ocean bottom seismometers). The geological and geochemical significance of remotely sensed features can be determined by precision sampling from submersibles and deep ocean drilling, with subsequent analyses using modern analytical instrumentation.

Marine geosciences are at a point where these new techniques can be integrated and utilized in major new programs to provide a comprehensive understanding of the processes which create and modify 70% of the earth's crust and which have controlled global environmental changes for the last 150 million years. The basic scientific manpower, theory, and technology exist for such programs. The present status and future trends for the five major program areas at existing support levels are summarized below.

1. Structure and Evolution of Continental Margins. The use and development of multichannel seismic techniques, swath-mapping, sonar systems, and seismic stratigraphic analysis have lead to new conceptual models of margin formation and evolution. On a few passive margins, such techniques have been coupled with heat flow, gravity, and sediment analyses to quantify faulting, crustal stretching, and subsidence which accompany continental rifting. Limited study of active margins has begun to clarify the process of continental accretion and provided unexpected evidence of crustal erosion.

The geological structure of the transition from ocean to continent is a direct result of, and varies with the processes causing rifting and subsidence (passive margins) or convergence and uplift (active margins). A major limitation is the lack of field data from these contrasting tectonic areas to construct and constrain geologic models.

A principal aim of future work is to provide crustal structure profiles at margins that differ in their physiography, sediment history, and tectonic style. Multichannel seismic experiments and ocean drilling will be part of studies of margin evolution that include lithologic and acoustic stratigraphy, structural analysis, subsidence analysis, and heat flow, gravity, and magnetic measurements. Correlation and integration with onshore geological studies will be required. This program is of fundamental geologic interest, but it is facilities-limited. Therefore, a major increase in support for this program area is requested as part of the Tectonics and Structures of Submerged Continental Margins component of the Global Program.

2. Tectonics and Structure of Midocean Ridges and Basins. Studies using multibeam bathymetric systems, side-scan sonars, navigated cameras, and research submersibles have provided new perspectives on the complex and poorly understood spatial and temporal scales of tectonic and volcanic processes along ridge crests and transform faults. Ridge crest reorganization and migration, changes in spreading rate, and fracture zone orientation can imprint the ocean crust with a complex structural and geochemical signature. Episodic volcanism may control both distribution of ridge crest morphologies and hydrothermal vents. Major limitations are a lack of knowledge of the internal structure of ridge systems, including the shape and distribution of magma chambers, and the spatial and temporal scales of volcanic activity and faulting which are needed to constrain dynamic models.

A major goal of future work is to provide a three-dimensional view of the structure and evolution of spreading ridges and fracture zones including closely-spaced surveys at critical locations using detailed bathymetric, magnetic, seismic, and heat-flow measurements. Complementary studies in off-axis, old ocean basins will examine effects of plate motions and geologic age on lithosphere chemistry and rheology. This area is also of basic scientific importance and is also facilities-limited. Therefore, the Oceanic Lithosphere component of the Global Program on Ridge Crest Processes provides for significant new efforts in this program element.

3. Geochemical Evolution of the Oceanic Crust. One square kilometer of new seafloor is created each year along midocean ridges. Research on this process and the resulting volcanic products has documented the large-scale geochemical heterogeneity of the crust and upper mantle; the rate of chemical and heat exchange between the ocean, oceanic crust, and mantle; and secondary mineralization of the crust as it ages. Application of modern analytic techniques for isotope and trace element variations provides insight into magma evolution, mixing processes, and thermodynamics of the volcanic system at ridge crests, back-arc basins, and seamounts. Detailed studies of the geochemistry of hydrothermal vents are relating the composition and structure of oceanic crust to the nature and origin of associated mineral deposits, though studies are limited by the lack of adequate control on chemical and thermal fluxes.

A major emphasis of future work is to couple detailed geochemical sampling and analysis with studies of the spatial and temporal scales of seafloor creation and evolution. Such studies will require coordinated and comprehensive geochemical analysis of samples recovered by dredging, submersibles, and crustal drilling. These studies will examine chemical heterogeneity produced by overlapping and propagating spreading centers, the location of transform faults and mantle plumes, and magma chamber evolution. This significant new effort is proposed as part of the Ridge Crest Processes component of the Global Program.

4. Fluxes, Transport, and Deposition of Marine Sediments. Approximately 40% of all sediments occupying the major global sedimentary reservoirs are found on the continental slope and rise and in the deep ocean. These sediments reflect a wide variety of complex and often interacting sources from continental erosion and pelagic productivity to volcanic eruptions and deep sea hydrothermal activity. Transport, deposition, and, often, subsequent erosion of these sediments are directly coupled to surface and deep ocean current systems and modified by the long-term history of global sea level.

Recent research has concentrated on (1) developing geochemical tracers which allow sedimentary components to be partitioned between source functions; (2) first-order studies of sediment supply and alteration through use of sediment traps and surface sediment analyses; (3) use of high resolution side-scan sonars and reflection profiling to study dynamic processes which transport and erode sediments; and (4) use of the preserved record to model global geochemical cycles of carbon, sulfur, and other elements.

Although first-order models of many of these processes are available, a major limitation to advancement is a lack of integrated field data sets incorporating comprehensive studies of source, transport and flux, and depositional controls. Increased support for such studies on continental margins are included as part of the Coastal Ocean Dynamics and Fluxes subinitiative. Predictability of regional sedimentary sequences and their acoustic stratigraphy, the resistance of sediment deposits to erosion or dissolution, slope stability along continental margins, and the origin of microtopography are still poorly understood.

Future emphasis will be on geochemical processes in the benthic boundary layer which modify terrigenous and biogenic material before its incorporation into the geologic record. Such studies will be coupled to ocean flux studies assessing production, transport, and dissolution of biogenic and inorganic material in the water column. Funds are included in the Open Ocean Fluxes sub-initiative for increased geochemical studies in this area. Efforts under the Land/Sea Interface program in Biological Oceanography will similarly complement this activity.

Additional emphasis at the current program level will be directed to effects of in situ reactions within sediments and their influence on physical properties, pore fluids, and sediment layering and chemistry. Enhanced support for a new Long Coring Facility is requested to improve sampling quality and recovery for sedimentary analysis.

5. Geologic and Climatic History of the Oceans. Paleoclimatology has emerged as a separate and important discipline. Study of microfossil assemblages, coupled with their geochemical signatures, has provided a new tool for examining changes in global climate and ocean circulation. Projects such as CLIMAP and SPECMAP have attacked the most recent portion of the geologic record and uncovered the relation between orbital forcing and the Pleistocene ice age. Samples from the Deep Sea Drilling Project have been used to document gradual decay of global climate and resulting formation of ice sheets during the last 60 million years (e.g., the CENOP project).

Other significant advances have been made in understanding ecology of marine organisms, the history of surface and deep water production and circulation, the global carbon cycle, and changes in the chemistry and biologic productivity of the global ocean. Most recently, theories of extraterrestrial impacts and their relation to biotic evolution are being examined in the context of global environmental conditions preserved in marine sediments.

Major goals of future work include detailed studies of specific geologic intervals to establish temporal relations between oceanographic, climatic, and tectonic events; improved understanding of the resolution of the oceanographic record preserved in fossil assemblages through studies of modern organisms and their environment; an increased emphasis on determining the history of the carbon cycle and its relation to climatic change; and use of integrated data sets to model ocean circulation and climate. Enhanced support for analyses of samples collected by the Ocean Drilling Program is requested (see below).

II. Critical Needs of the Core Program

The areas of critical need in Ocean Sciences Core support are all relevant to the Marine Geology and Geophysics Program. In particular, support for three aspects of this research program are urgently needed to continue recent scientific advances and respond to technological improvements. Each crosses several programmatic areas described in the preceding section. These are:

1. Ocean Drilling Program Sample Analyses. Support for postdrilling analyses of samples from the Ocean Drilling Program (ODP) is provided by established disciplinary programs at NSF - mainly Marine Geology and Geophysics. The drilling program includes major sampling programs for carbonate reef formation and carbon cycles in the oceans, controls and timing of glacial cycles, early rifting history of the Atlantic Ocean, geochemical and thermal evolution of oceanic crust, evolution of the Mediterranean Sea, mineralization processes, sedimentation regimes, and tectonics of ocean ridge systems and continental margins. Sample sites range from the Norwegian Sea through the Atlantic Ocean to the Weddell Sea off Antarctica followed by future work in the Indian Ocean and Pacific margins.

The success of the drilling program requires a strong sample analysis effort and without enhanced support it will be difficult for the U.S. research effort to maintain its leadership position in this international program. Funding at \$1M per year is required to establish and maintain effective levels of research.

2. Long Coring Facility and Sedimentary Processes. Approximately 40% of all sediments are found on continental margins and in the deep ocean. The marine sedimentary sequences, in general, are more continuous than land deposits; are the ultimate sink for terrestrial, pelagic, and deep-sea hydrothermal particulate materials; and are the recording medium for past global environmental and climatic changes.

Large continuous samples from differing regional settings are required to meet research goals. Funding is needed for acquisition and operation of an instrumented piston corer system and handling equipment capable of taking 50-meter-long, 10-centimeter-diameter cores from a number of research vessels. A Long Coring Facility (LCF) will provide sufficient penetration capability to resolve major sedimentary, diagenetic, and geochemical processes. It will complement the deep penetration capabilities of the Ocean Drilling Program and extend standard piston coring techniques by a factor of three.

Preliminary engineering design of a prototype system is complete. The LCF corer will find immediate use for paleoclimatic studies along continental margins, in sediment transport and microtopography studies, and in determination of geochemical gradients in ocean sedimentary basins. In FY 1989 and FY 1990 \$0.9M will be required for construction and testing. Operation costs are estimated at \$0.6M annually during the period FY 1991-96.

3. Geochemical Instrumentation. During the past decade marine geosciences research has evolved from reconnaissance studies to quantitative studies examining various aspects of paleoceanographic and plate tectonic models. This transition has highlighted the need for modern analytic instrumentation. An example of research opportunities that require improved analytical systems is polymetallic sulfide mineralization on oceanic ridge systems. The complex series of geologic, geochemical, and physical reactions involving high temperature seawater-rock, mineral fluids-rock, mineral fluids-cold seawater, and secondary mineralization and magmatic processes are a formidable challenge.

In the past, interpretations have all too often been frustrated by lack of a comprehensive approach, and critical data have been missing because adequate instrumentation was not available. New state-of-the-art, automated instruments with on-line computers and real-time data correction, reduction, and archiving capabilities, as well as a new generation of instruments with multielement or isotope detection capabilities, are needed. These include electron microprobes, ion probes, x-ray diffraction and fluorescence units, gas and solid source mass spectrometers, acceleration mass spectrometers, emission and absorption spectrometers, microprobes, and transmission and scanning electron microscopes.

No oceanographic institution has the instrumentation, facilities, or necessary expertise to undertake all the techniques identified. It will be necessary to expand present analytical facilities and develop regional and national capabilities to provide for the comprehensive studies needed. Funding is required for a six-year program totalling \$4.2M to upgrade (and utilize) instrumentation capabilities at oceanographic institutions. Additional funding for acceleration mass spectrometry is also needed, but it is budgeted as part of the facilities needed for the new initiatives. It is described in the Chemical Oceanography section of this document.

III. Marine Geology and Geophysics Component of the Global Program

The Ocean Lithosphere Studies component of the Global Program provides for a broad research effort based on modern technology to be directed toward understanding the dynamics, structure, evolution, and origin of ocean basins. It has two major aspects: (1) Tectonics and Structure of Submerged Continental Margins and (2) Ocean Lithosphere and Ridge Crest Processes. They focus respectively on ocean-continent transition zones and tectonics and on hydrothermal processes at ocean ridge systems. Together they provide a balance between (1) examining crustal formation processes responsible for the basic structure of 70% of the earth's crust and the associated biological and chemical questions, and (2) determining the processes of formation of oceanic sedimentary basins, destruction of oceanic crust, and aggregation of continents. Both components share the need for expanded facilities and their application. The approach to these problems balances upgraded and expanded field programs with improvements in laboratory equipment and development of new in situ measurement technologies.

1. Ocean Lithosphere Studies

a. Tectonics and Structure of Submerged Continental Margins

The transition zones between continents and oceans represent the boundary between the two major physiographic provinces on our planet. In some cases they are also past or present boundaries of the lithospheric plates forming the earth's surface. A much deeper understanding of the structure, tectonics, and dynamic evolution of these fundamental geologic features is within our grasp. The basic scientific manpower, theory, and technology exist for developing a comprehensive understanding of continental margins.

Some of the major questions to be addressed are:

- What are the geologic units underlying passive and active continental margins? How is their geology coupled to formation of ocean-continent boundaries? What are the dominant tectonic, geochemical, and thermal processes?
- How does the geology vary along continental margins? What are the differences between old and young margins, island arc and trench regions, fast and slow convergence sites, and thick and thin sedimentary sequences? What is the coupling to adjacent geologic provinces, to onshore basins and trenches?
- What causes initial rifting? How are conjugate sites on the opposite side of ocean basins related? What are the controlling factors for subsidence rates, sediment accretion rates, thermal histories, and regional basin formation?

To answer these questions modern geophysical, geological, and geochemical methods and equipment for measuring and interpreting the physical properties of crustal structure are needed. A primary technique is multichannel seismic profiling with large numbers of detectors and large receiving apertures. The Large Aperture Seismic Experiment (LASE) showed that multiship techniques can map the deep structure of the margins. A major limitation is the lack of field data from contrasting tectonic areas to construct and constrain geologic models and the lack of state-of-the-art multichannel seismic systems.

An early thrust of the program is to acquire seismic data on the continental margins with tuned-source arrays and high-speed digital recording systems. Sufficient resources will be used to maintain effective data acquisition and data analysis centers along with the critical mass of scientists, technicians, and students required for operations. An expanded number of seismic experiments (\$2.7M in FY 1989, \$6.2M in FY 1990, and increasing to \$12M by FY 1992) for studying deep structure in contrasting regions will be integrated with lithologic and acoustic stratigraphic analysis, structural analysis, subsidence analysis, and heatflow, gravity, and magnetic measurements. The initial studies will use upgraded capabilities of existing ships followed by a transition to a proposed new research ship in FY 1991.

An additional requirement is correlation of marine geological and geophysical studies with onshore geologic studies of the Continental Lithosphere program and offshore drilling by the Ocean Drilling Program. Geologic samples from continental margins will provide controls on the age and nature of basement, on age correlations for seismic reflectors, on biostratigraphic data for subsidence models, and on the composition and facies of geologic sections. Other significant measurement techniques include using arrays of ocean-bottom seismometers, the Long Coring Facility, and upgraded laboratory facilities for geophysical, geological, and geochemical analyses of data and samples.

b. Ridge Crest Processes

Oceanic ridges are a major component of the dynamic geologic system that forms, modifies, and changes the surface of the earth. They are the source of major transfers of heat and chemical elements from the earth's interior to surficial geologic layers and into the oceans by volcanic and hydrothermal processes. Active "vent systems" also support specialized biological communities that draw a significant part of their energy needs from geochemical fluxes.

Much more is known about kinematics of seafloor spreading than about plate mechanics, their physical and chemical properties, or the forces acting to drive the plates. These questions plus their geological, chemical, and biological effects remain unresolved because of a lack of state-of-the-art observational data to test hypotheses and speculations. A major limitation is the lack of knowledge of the internal structure of ridge systems and the spatial and temporal scales of volcanic activity needed to constrain dynamic calculations.

The objective is to provide integrated geochemical and structural models defining spatial and temporal scales of seafloor creation and evolution. Particular emphasis will be directed to developing techniques for long-term monitoring of hydrothermal vent systems to quantify their full geochemical cycle.

Some of the major questions to be addressed are:

- How does the ocean lithosphere respond mechanically to large surface loads, to compression, to bending, to stretching? With an understanding of these factors, what can we learn about deeper processes in the earth, such as mantle convection, by looking through the "ocean lithospheric window?"

- What are the driving mechanisms for seafloor spreading? How does crustal accretion vary with time? What are the local scales of accretion and tectonics in space and time? How are volcanic processes coupled to hydrothermal circulation at midocean ridges? What are the controlling factors on sulfide mineralization and the extent of deposits? What is the variability and alteration of oceanic crust as it moves off-axis?
- What are the chemical and thermal properties of hydrothermal fluids from vents and what is their role in the mineralization process? What is the contribution of vent fluxes to chemical balance of the oceans? What chemical reactions occur? What is the relation between fluids and biologic communities?

Answering these questions requires modern detailed survey capabilities (e.g., Seabeam, Seamarc, *Alvin*) for expanded field programs to determine the history and scale of crustal accretion (\$1M in FY 1989, \$2M in FY 1990, increasing to \$6 in FY 1992). Research submersibles must be used to mount integrated geological, chemical, and biological studies to examine a spectrum of representative sites including high and low temperature fluids, seamount localities, and sedimented and unsedimented regions. In situ instrumentation for long-term monitoring of hydrothermal vents and crustal accretion must be developed and deployed (\$2M per year beginning in FY 1989).

These systems must include flow meters, chemical and thermal sensors, strain gauges, and ocean floor seismometers. Improved techniques for multichannel seismics must be used in selected areas to conduct experiments focused on determining thermo-mechanical properties of the oceanic lithosphere under varying conditions of age, stress/strain, and thermal regimes (\$1M in FY 1989 and \$2M/year from FY 1990 through FY 1996). For complete integration of spatial, temporal, and in situ processes, crustal drilling by ODP on bare rock hydrothermal sites is required. An appropriate set of instrumented holes would form a long-term natural laboratory.

The additional funding requested is essential if existing capabilities are to be upgraded. Use of new multichannel seismic, side-scan sonar, Seabeam and submersible systems in integrated studies of geochemical and mineralization processes requires new resources. Development and implementation of in situ monitoring systems for geophysical, tectonic, chemical, volcanic, and biological changes require support beyond that available within current support levels. Application of these new suites of observational systems over the next ten years will lead to greater understanding of these basic elements of the earth-ocean system.

2. Related Programs

Research being conducted under two other subinitiatives is important to the study of sediment transport and fluxes, production and processes involved - the flux of organic materials to the seafloor and the fate of biogenic materials. These programs are Open Ocean Fluxes and Coastal Ocean Dynamics and Fluxes and funding requirements for these programs accompany their program descriptions.

IV. Funding Requirements

Funding requirements for the marine geology and geophysics program, including the core program, critical needs, and major new programs are presented in Table D in Section IV.

E. Ocean Drilling Program

I. Core Program

The Ocean Drilling Program (ODP) is an international research program organized to explore the structure and history of the earth beneath the ocean basins. The focus of ODP is to provide core samples from the ocean basins, facilities for the study of these samples, and to provide downhole measurements (logging) and experiments to determine in situ conditions within the earth's crust.

The major scientific themes addressed by ocean drilling, identified in the first Conference on Scientific Ocean Drilling (COSOD) report, include:

- Processes of magma generation and crustal construction at ridges. What is the character and composition of the deep portion of the oceanic crust?
- Configuration, chemistry, and dynamics of hydrothermal systems. What are the dimensions and characteristics of hydrothermal systems at ridge crests versus those on ridge flanks? How does overlying sediment cover, or the lack of it, affect these hydrothermal systems?
- Early rifting history of passive continental margins. What is the shallow and deep structure of stretched and normal faulted margins versus those characterized by excessive volcanism?
- Dynamics of forearc evolution. What are relative motion, deformation, and pore water characteristics of sediments at accreting and erosional margins?
- Structure and volcanic history of island arcs. What are space and time relationships of forearc subduction, accretion, and erosion; and of backarc spreading, compression, and volcanism?
- Response of marine sedimentation to fluctuations in sea level. Which stratigraphic sequences and intervenin unconformities represent fluctuations of sea level, and which represent vertical tectonic motion? What is the response of deep-sea sedimentation to fluctuations of sea level?
- Sedimentation in oxygen-deficient oceans. What are the ocean circulation, paleoclimate, and potential hydrocarbon characteristics associated with black shale deposits?
- Global mass balancing of sediments. What are best estimates of the world sediment mass and composition balances in space and time?
- History of ocean circulation. How do patterns of ocean circulation respond to changing ocean boundaries, e.g., changing ocean size, the extent of shallow continental seas, and the opening and closing of oceanic passages?

- Patterns of evolution of microorganisms. How has the process of evolutionary change proceeded in marine organisms?
- History of the earth's magnetic field. What is the nature of the magnetic field during a magnetic reversal? What is the detailed history of magnetic reversals and changes in the intensity of the magnetic field?

A second COSOD meeting (COSOD II) to evaluate the progress of ODP to date and to make recommendations for scientific and technological objectives in the 1990's is planned for Strasbourg, France, in July 1987.

The ODP is funded by the U.S. National Science Foundation (NSF) and by partners which currently include Canada, France, the Federal Republic of Germany, Japan, the United Kingdom, and the European Science Foundation representing thirteen Western European countries. Support for general operation of the drillship *JOIDES Resolution* and related science services is from comingled funds (U.S. plus international partner contributions) while direct support for U.S. scientists to participate in precruise planning, sea-going operations, and postcruise research is a national responsibility. The ODP is managed by Joint Oceanographic Institutions, Inc. (JOI) as prime contractor to NSF.

The overall direction of the program is established by the Joint Oceanic Institutions for Deep Earth Sampling (JOIDES) which provides planning and program advice with regard to scientific goals and objectives, facilities, scientific personnel, and operating procedures. The JOIDES Office provides support for the JOIDES Executive and Planning Committees and for the science advisory structure in general.

Texas A&M University (TAMU) is the Science Operator for ODP and manages the operation of the drillship, including the planning and implementation of cruises. The Lamont-Doherty Geological Observatory (LDGO) manages the wire line logging operations for obtaining measurements in the drill holes. Sample and data banks are maintained by TAMU and LDGO for cores and downhole measurement collected by ODP.

Research and planning activities that are directly related to specific drilling objectives or that are required to meet broad-based U.S. research community needs (national needs) are coordinated by the U.S. Science Advisory Committee (USSAC). These efforts include: (1) planning activities, including U.S. participation on JOIDES panels and regional or topical workshops; (2) recommendations for shipboard scientific participants, (3) syntheses of existing topical and regional data to meet defined drilling objectives, (4) development of downhole tools and instrumentation for general use in the drilling program, and (5) site specific surveys for safety or unique siting requirements on defined drilling legs.

Regional geological and geophysical field studies required to develop drilling proposals and specialized downhole geophysical or geochemical experiments are supported by the ODP Program Office of NSF from unsolicited proposals. Based on the results of these studies, planning panels solicit future drill sites. Individual studies address the major problems outlined by the Marine Geology and Geophysics Program (i.e., Structure and Evolution of Continental Margins; Tectonics

and Structure of Mid-Ocean Ridges and Basins; Geochemical Evolution of the Oceanic Crust; Fluxes, Transport and Deposition of Marine Sediments; and the Geologic and Climatic History of the Oceans). The ODP field programs build on and complement the marine geology and geophysics field efforts and provide the data required for U.S. scientists to translate their research goals to specific drilling objectives.

A number of different types of downhole studies are supported. These include the analysis and interpretation of the data from the ODP shipboard logging program; development and operation of instrumentation required for downhole experiments together with the analysis of the data; and feasibility studies of new general use downhole instruments or techniques. The results of the studies together with analyses of recovered geologic samples are crucial to converting the drillhole work to solutions to the scientific questions and problems.

II. Critical Needs of the Core Program

Borehole geochemical and geophysical measurements permit extrapolation of drillhole results well beyond the sides of the wellbore. Experiments such as oblique seismic reflection sounding, using a geophone clamped in the wellbore, give a picture of the regional lithology and structure for several tens of kilometers. Downhole sampling of formation water, especially in holes which penetrate the plumbing systems of hydrothermal regions, allows the measurement of the material balances within the oceanic crust. Downhole measurements of physical properties show the natural state of stress in the ocean floor and indicate the modes of response to that stress by fracture and flow. These measurements require the development of expensive instruments and their deployment in the drillhole. Because of the peculiar requirements for deployment in the drillhole (narrow diameter, high pressure, high temperature, etc.) these instruments must be substantially modified from more conventional instruments used in other studies. The costs of this enhancement are expected to be \$1.5M in FY 1989 increasing to \$2.1M by FY 1996.

Regional geological and geophysical field studies provide the fundamental information base for the formulation of drilling proposals. The U.S. effort in regional studies supplies the bare minimum of well-surveyed regions. The appropriate level is considerably higher. There should be two well-studied regional drilling targets for each drilling leg to insure that the drillship is used on the most important and interesting targets. The costs of these efforts are expected to be \$2M in FY 1989 with a 10% annual growth for the remaining life of the Ocean Drilling Program. Approximately half of these funds will be expended on ship time and half on scientific operations.

Critical needs and initiatives in other ocean science programs are important to ODP. In order to ensure that samples are effectively used, ODP has a collaborating interest in the Marine Geology and Geophysics Program (MGG) enhancement for ODP sample analyses. Similarly MGG efforts in the Ocean Lithosphere Studies are important to ocean drilling objectives and represent opportunities to collaborate with nondrilling investigators. The Open Ocean Fluxes program is also important to ODP as it will demonstrate the relationship between the sedimentary record of the environment and environmental parameters which paleoceanographers are attempting to understand using ODP cores. These programs provide new insights into geological processes and problems which will develop into new drilling targets for ODP. Exchange of ideas between nondrilling and drilling science operates in both directions and benefits both.

The present capabilities of the drillship, while impressive, are limited. The ship is not able to drill in any situation where uncontrollable flow might occur in the well bore. This limitation is due to the lack of a riser and well control system. The drillship was chosen because of its ability to support these systems, but they are not presently installed. The JOIDES planning structure has begun to investigate scientific opportunities presented by the addition of a marine riser and well control system. Initiation of engineering studies and equipment acquisition is expected to require \$1.1M in FY 1989 and \$2M in FY 1990. In FY 1991, shipyard and material acquisition costs are estimated to be \$10M. A riser drilling program starting in FY 1992 is expected to have an incremental cost over standard operations costs of \$5M initially increasing to \$6.2M by FY 1996. Because ODP costs are shared by the U.S. and the international partners, the U.S.-appropriated funds required for this initiative are approximately 55% of the total or \$0.6M in FY 1989; \$1.1M in FY 1990; \$5.5M in FY 1991; and \$2.8M in FY 1992, increasing to \$3.4M in FY 1996.

III. Funding Requirements

Summary budgets for international operations, core programs for science support, and areas of critical need for future advances are included in Table E of Section IV.

F. Oceanographic Technology Programs

Long-range Planning

I. The Core Program

The field of ocean science research is undergoing rapid evolution and advances in all of its component disciplines. In the past decade or so, our understanding of the seafloor and ocean basin geology has been transformed by discovery of and advances in tectonic theory. The discovery of unique vent communities at great depths has altered views and insights about deep-sea biology and has revolutionized studies concerning aspects of cell physiology and other biological phenomena. Our understanding of macro- and mesoscale ocean circulation processes has advanced to such a level that global perspectives can finally be developed, and our understanding of oceanic chemical fluxes and reaction mechanisms is providing new tracers for biological and biochemical processes.

Advanced technology plays an important role in contributing to the productivity and maturation of the ocean sciences. Introduction of critical new technologies to the field is a common theme in the study of global change and is central to the Global Ocean and Lithosphere initiatives. The core research programs and their enhancements need continued and expanded progress in instrumentation, facilities, data management, and new observing systems. The ocean sciences are at a point where new technologies must provide critically needed tools and techniques for the ocean science research programs to develop comprehensive understanding of global change.

The multidisciplinary core program in oceanographic technology provides technical services, instrumentation, and facilities support to the ocean sciences. It is organized around two elements - oceanographic instrumentation and shipboard technical support.

A. Oceanographic Instrumentation Program

This core program provides support to institutions for the acquisition of shared-use scientific instrumentation to be placed in an equipment pool available to all users of the facility, be it a research vessel or shore based laboratory. Overall research support capability of the institution and its ability to make effective use of the requested instrumentation for conducting a number of NSF-sponsored research projects are main criteria for program support.

Instrumentation acquired under this program may vary greatly; new capabilities for meeting research requirements have recently included acoustic doppler current profilers, seismic reflection systems, image analysis systems, and advanced shipboard computers.

B. Shipboard Technician Support

This core program provides technical assistance to users of the academic research vessel fleet. It includes at-sea maintenance and repair of shared-use scientific equipment, liaison between scientific staff and ship's crew, and shore-based maintenance, calibration, and scheduling of equipment. Because there is increasing collaborative and cooperative use of research vessels, an important role for the program is to provide guidance and assistance to visiting investigators from outside the ship-operating institution.

Management of this support program entails close interaction with the Ship Operations Program in following the numerous iterations of the research vessel operating schedules. Interactions with the technical support managers at the various institutions is also required to insure some uniformity among the services provided on different vessels. Interaction with the science support programs and the individual ship users is also required to evaluate and monitor the effectiveness of services provided.

As the technical sophistication and complexity of sea-going systems increase, the requirements for technical support centers are also increasing. More and larger institutional centers are projected as part of the new Global Ocean and Lithosphere Studies initiatives.

II. Critical Needs of the Core Program

The most important of the critical needs under this program are in the areas of in situ and intelligent ocean sampling systems.

A. In Situ Measurement Systems. Despite the fact that ship and manpower costs will continue to increase, ocean science can broaden the scope of data acquisition without major increases in costs if more effective measurement systems can be developed. Autonomous vehicles may be one solution; others include fast response profilers; large, highly instrumented towed arrays to increase the data acquired per ship-hour; and expendable instruments that may be deployed from ship or aircraft and telemeter data to central locations. As the trend in ocean measurements continues from small-scale, short-term to large-scale and long-term, better sensors will be necessary. Although diverse sensors exist, many require substantial power and are very delicate. If the requirement for long-term, unattended measurement is to be met, research must be directed towards improving existing sensors and the development of entirely new sensors and sensor systems with an emphasis on low power, high stability, robustness and reliability. Funding of \$1.5M in FY 1989 growing to \$3.1M in FY 1996 is required for this effort.

B. Intelligent systems. Research in the field of "knowledge-based computing" has now evolved to the state that it is feasible to apply some fundamental artificial intelligence (AI) concepts to problems of ocean science. One can now consider programming "judgement" into instrument and vehicle systems. There is a need to establish a development effort for applying knowledge-based computing to ocean research.

Current trends in ocean science require placing data acquisition systems in the ocean, unattended, for long periods of time. An AI control system designed to handle a wide range of unanticipated transient or steady state events could improve the quality of the data gathered. It could control sampling rates, dynamic range, parameters measured, sensitivity of measurement, etc. as well as handle any reliability problems associated with sensor or equipment failure. The data system could be designed to behave as if the best of human experts were onsite controlling the experiment. The addition of symbolic line-of-reasoning methodologies to well developed mathematical techniques could provide new concepts for instrumentation and measurement.

Remotely operated and robotic vehicles are candidates for ocean surveys, such as bathymetry and photo surveys, and the measurement of specific parameters in time and space. The robotic vehicle, almost by definition, will need the high degree of decision making capability that research submersibles now have in pilots and scientists. They could be capable of extended submerged operations following launch from shore or ship to home on any desired target. The same logic can apply equally to surface platforms. An unmanned surface platform would require the ability to make decisions about its environment as well as its current performance. It must be able to contend with a wide variety of circumstances during a long unattended term, and it must have the ability to manage and plan the function of its instruments in response to a changing environment.

Funds required to meet these needs are \$2M in FY 1989 with an approximate doubling of this effort by FY 1996 (\$3.8M).

III. Oceanographic Technology Component of the Global Program

A pilot program in oceanographic technology development was initiated several years ago. It demonstrated that this component is essential to overall productivity of the ocean sciences, and it is a key component of the global program. During the next decade, continued advances in ocean sciences will be significantly influenced by introductions and further developments in at least four major technologies: satellite-based remote observing systems, ocean sample collecting systems, new ocean structures, and supercomputers. With the enhancements requested, these technologies will help meet the requirements of the major new global-scale ocean sciences initiatives.

A. Remote Measurements: The prospect of synoptic measurements on global scales from satellite altimeters, scatterometers, and microwave radars has excited the ocean science community for some time. The Long-Range Plan for the Ocean Sciences depends upon an effective and "easy to access" program with satellites, such as NROSS and TOPEX. While much of the costly technology for satellites is appropriately being developed under the aegis of NASA, it is unlikely that NASA will develop technology to support the needs of effective networking, processing, and analysis of oceanographic data. Funds to meet these needs are included in the Global Ocean Studies initiatives.

In addition to satellite measurements, but equally important, are remote measurements using techniques such as optic and acoustic sensors, autonomous vehicles, and deep ocean observing networks. Engineering and technical requirements of these systems for basic research purposes will fall entirely upon the ocean community.

B. Sample Collecting Systems: In situ measurements of many ocean properties are possible and highly desirable, but there are many others that require laboratory analysis of samples collected at sea. Samples are required, not only to verify and calibrate remotely obtained in situ measurements, but also to describe features being studied. Many water, particulate, and biological sampling systems now in use must be operated blind, towed over poorly defined areas at the ends of long cables. Sampling systems that can better sense their environment and be selectively controlled for appropriate time and space scales need to be developed. Such systems could be tethered to ships by cable or integrated into autonomous vehicles or moored arrays.

C. Ocean Structures: Ability for long-term emplacement of instruments on the seafloor or tethering to the bottom by an anchor is increasingly needed by many ocean programs. Bottom landers are growing larger and more complex. There are still many areas of the deep ocean where mounting of such devices is impossible or risky because of high energy conditions in the near bottom and strong shears within the water column. New materials and ideas need to be developed and tested so that future ocean science programs may have reliable and long-lasting structures for mounting experiments, such as those required for the hydrothermal vents program in the Ocean Lithosphere initiative.

D. Supercomputers: Ocean science investigators are increasingly accessing modern supercomputers. The FY 1985 NSF initiative to establish an ocean modeling facility at NCAR and to provide broad-band communications links is a vital first step. The field of Geophysical Fluid Dynamics (GFD) has made signal contributions to modeling and prediction of atmospheric behavior. Major inroads into critical issues concerning ocean circulation will similarly be made with the advent of new supercomputer capabilities. They will profoundly influence interactions between theory and observation in ocean physics. In this plan it is assumed that the supercomputing capability for ocean sciences will continue to expand as modeling needs of all of the sub-disciplines grow. Management in OCE will remain with the disciplinary programs, but Ocean Technology will continue to support basic hardware and communications equipment acquisition.

It is increasingly apparent that ocean science investigations are highly dependent upon the availability of sophisticated and appropriate technology. To the future needs, outlined above, can be added the increasing need to access, on a broader scale, the remotest parts of the vast reaches of the ocean. Data gaps in such locations as the polar oceans, the Indian Ocean, the South Atlantic and Pacific Oceans, and deep ocean basins and trenches increasingly impede formulation of large-scale theories of ocean and earth phenomena. Cost-effective technology to access and sample these regions is lacking. Research and development focusing on expendable systems, air-launched systems, remote sensing systems, and intelligent mobile systems could help to meet research initiatives and enhancements discussed in the Long-Range Plan.

IV. Funding Requirements

Major growth in this program area is recommended as an essential part of the new global program. Support for advanced technology and systems is directly coupled to specific initiatives under this program. A summary budget for the core programs, areas of critical need, and the global studies is included in Table F of Section IV.

G. Ship Operations, Shipboard Scientific Equipment and Ship Construction/Conversion Long-Range Planning

I. The Core Program

The U.S. academic research fleet is supported through a joint effort of several Federal agencies. The National Science Foundation is the key agency among these and conducts a comprehensive program for support of ship operations, development and acquisition of shipboard scientific equipment, and ship construction/conversion.

The Ship Operations Program provides funds for operation and maintenance of research vessels used in support of NSF-funded scientists. Ship Operations support includes: crew and marine staff salaries; maintenance, overhaul, and repair; insurance; direct operating costs such as fuel, food, supplies, and pilot fees; shore facilities costs directly related to ship operation; and indirect costs. Ship Operations is an integral part of the core program. It supplies support for operation and maintenance of platforms essential to ocean-going research. NSF supports each year about 170 science projects requiring about 3,700 days at sea and about 40,000 scientist days on 25 ships. As a result, NSF supports about 70% of the total operating costs of the U.S. academic fleet.

A modern and efficiently operated academic fleet is essential to field programs in the ocean sciences, both for the core ocean science programs and for the global program. This plan outlines the requirements for NSF to take the lead in equipping and assuring effective operation of the academic fleet. The plan identifies the NSF role in upgrading and modernizing a research fleet largely built during the 1960's and now requiring extended operational and scientific capabilities. This plan is based on a careful evaluation of this fleet, done with assistance from UNOLS and the National Academy of Sciences.

II. Critical Needs of the Core Program

The U.S. academic fleet has been the cornerstone of productivity in the ocean sciences. There are critical needs that require appropriate budget augmentations to maintain an effective and scientifically viable field science program in the ocean sciences. Two priority areas of the core program require special attention: (1) shipboard scientific equipment and (2) upgrading and modernization of the academic fleet.

A. Shipboard Scientific Equipment

The Shipboard Scientific Equipment Program provides funds for ship equipment deemed essential to proper and safe conduct of ocean science research. This Program provides support for such items as deck equipment, including winch systems for deployment and retrieval of scientific instruments; navigational equipment, such as radars, gyroscopes, and earth satellite receivers to pinpoint the locations of research sites; communications equipment, including radio and satellite transceivers for voice and scientific data communications; and other equipment, such as motorized workboats for transporting scientists to and from their operations.

In recent years, the Shipboard Scientific Equipment Program has been responsible for significant improvements in the ability of academic fleet vessels to support research. Improved communications and navigation technology (such as INMARSAT and GPS, respectively) is being added to the fleet. Special emphasis has been placed on upgrading deck equipment (such as CTD winches and cranes) to handle the larger and increasingly massive instruments (such as rosette samplers and MOCNESS nets) which have come into wide use. This Program will continue these efforts in the near future and will coordinate them with modernization of onboard science laboratories and automation of data collection and analysis systems. Funding of \$0.5M in FY1989 increasing to \$1.7M in FY1996 is required for this effort.

B. Upgrading and Modernization of the Academic Fleet

In 1970, almost 70% of the academic research fleet was composed of ships which had been converted to research vessels. By 1985, this percentage had been reduced to less than 20% by replacing older converted ships with ships designed from the keel up as research vessels. The Ship Construction/Conversion Program provides funds for new ship construction; for conversion of ships to research vessels, when appropriate; and for refitting existing research vessels.

Since 1970, the National Science Foundation has funded construction of seven new research vessels -- *Calanus*, *Iselin*, *Oceanus*, *Wecoma*, *Endeavor*, *Point Sur*, and *Cape Hatteras*. Occasionally, it remains economically advantageous to replace an obsolete vessel with a conversion. A recent example was the NSF-supported conversion of an offshore supply vessel to become the R/V *Sprout*, replacing the aging R/V *Scripps*. Recent refittings have included the *Alpha Helix* (a new pilot house and modernized laboratories); the *Iselin* (interior spaces); and the *Cape Henlopen* and the *Warfield* (engine improvements). Funds required to meet these needs are \$2.2 M in FY1989 with an increase to \$3.1M by FY1996.

III. Research Vessels as Components of the Global Program

The capabilities of the existing research fleet must be substantially improved during the next decade if forefront ocean science research is to be successfully pursued. The ships of the research fleet have been and will continue to be essential to this pursuit. However, present demands of science require new, more capable research ships to replace aging existing ships, especially the largest ones. All reviews of the academic research fleet demonstrate that by the 1990's most present ships will be obsolete in terms of their capability to support the growing requirements of modern sea-going ocean science research. Better sea-keeping ability, higher performance, improved over-the-side handling arrangements, and modern, state-of-the-art shipboard laboratories are needed to meet these requirements.

The trends and patterns of the basic ocean science disciplines demonstrate the critical nature of the needs for substantially improved ocean-going, more science-capable vessels and platforms.

Ship and Science Requirements

The following summary of trends of future research is abstracted from a UNOLS report. The primary source documents for the research trends were the 1982 Report of the NAS Ocean Sciences Board, *Academic Research Vessels 1985-1990*, and the 1985 NSF/OCE Long-Range Plan for Ocean Sciences, *Emergence of a Unified Ocean Science*.

A. Physical Oceanography. Physical oceanography involves the study of mean and eddy fluxes of energy, heat, freshwater, chemicals, and gases horizontally and vertically throughout the oceans and exchanges at the ocean boundaries. In the coming decade, ships will remain the primary method of observing the oceans at high resolution by deploying, and, in some cases, recovering nontethered instruments. As research progresses, the instrumentation must become more sophisticated; this calls for state-of-the-art technology in cranes and winches, ship-to-shore communications, and shipboard computers.

A few decades ago, it was standard practice to infer ocean motions and mixing from limited measurements of water temperature, salinity, and perhaps oxygen and nutrient content. Today, physical oceanographers are using a variety of new and developing instrumental techniques (floats, moored arrays, acoustics) for direct measurements over an increasing spectrum of time and space scales. Coupled to this are water column measurements which are expanding greatly in density and type, including the use of stable and unstable isotopes and natural and man-made tracers. These expanding and diversifying measurement requirements point clearly to the need for larger ships with more laboratory, deck, and berthing space; increased shipboard data acquisition, processing, and analysis capabilities; better equipped and cleaner laboratories; and larger complements of scientists and technicians.

Physical oceanographic research complements chemical and biological studies. As the need increases for more interdisciplinary field work, so will the heavy demand for more laboratory space.

B. Chemical Oceanography. Future chemical oceanographic programs may be considered under the broad categories of tracers of ocean processes, exchange and fluxes, and reaction mechanisms.

Recent advances in laboratory analytical techniques enable a look at increasingly more stable trace elements and organic species that offer exciting possibilities as tracers of biological and biochemical processes. Oceanic distributions of many of these species are still largely unknown. An important aspect of these studies is the need for high density sampling and analyses in selected horizontal and vertical profiles. Many measurements are aliased because sampling frequency has been too sparse to represent the natural variability. The development of profiling tools and automated analytical techniques will be required for these studies.

Distribution of chemicals in the ocean is central to understanding fluxes that are taking place at important ocean boundary regions and within the ocean's interior. The ability to assess the climatic record or implications of pollutant dispersion is dependent on a knowledge of materials exchanged at the air-sea interface. This calls for sampling locations uncontaminated by the vessel or nearby environment.

Another aspect involves chemical fluxes at the seafloor boundary. Understanding of seawater-crustal interactions has been greatly enhanced by the recent study of fluids issuing from hydrothermal vents in midocean ridge areas. Analyses of these fluids provide important information on the chemical compositions of exchanges between the fluid oceans and the solid earth underlying them.

These studies require various experimental and sampling strategies, including in situ pumping and filtering, sediment trap deployment, in situ experiments on the ocean floor, and time-series sampling systems.

Marine chemists in the 1990's will need to perform chemical measurements and sampling with greater resolution in space and time than is now possible. They will give more attention to short-lived, unstable, chemical species responsible for chemical dynamics in the ocean. They must be able to perform real-time chemical analyses at sea and conduct more experimental studies at sea. A great deal of chemical oceanography has used ships as sampling platforms and returned the samples to shore laboratories for analysis. However, important investigations of chemical speciation and transient chemicals frequently can not be accomplished on stored samples. Future marine chemical studies will require analytical and experimental facilities at sea that equal those on land.

C. Marine Geology and Geophysics. Marine geoscience in the next decade will focus on:

- Close-up investigations of seafloor features with 3-D imaging, detailed measurements and sampling with manned submersibles, deeply-towed vehicles, and remote deep-swimming devices; and
- More powerful geophysical techniques for imaging the deep structure of the oceanic crust, margins, and lithosphere.

This research will require use of research vessels designed specifically for studying seafloor geology. The specialized instrument systems and activities that most profoundly influence the designs are:

- Large array multichannel seismic system: requires rigging for handling large air gun arrays and large, reinforced deck space aft to accommodate a 20-ton, 8-foot high, 15-foot wide streamer reel. The ability to tow multiple air gun arrays and/or streamers over a 50 to 100 meter thwartship span is important. The air guns require a minimum of four large capacity compressors that can develop pressures of >2,500 psi.
- Deeply-towed acoustic imaging system: requires a winch capable of handling 25,000 feet of electro-mechanical cable.
- Multibeam bathymetry: requires a "quiet" hull, sufficient beam to carry the hull-mounted hydrophone arrays, and, for some applications, a relatively high cruise speed (15 knots).
- Submersible: One or more of the geological ships should be able to carry and launch a manned deep submersible (e.g., *Alvin*).

- General station work: Launching dredges, cores, and instruments requires over-the-side frames and plenty of working deck space and clearance. Certain applications, such as bore-hole reentry, will require dynamic positioning.

D. Biological Oceanography. Biological oceanographic research in the next decade will focus on defining the structure and processes of ecosystems on scales ranging from the microenvironment of an individual to basinwide biogeographic distributions of populations and communities. Emphasis will be on filling major voids in the knowledge of particular ocean regions and of important dynamical processes which, until now, have been difficult to approach because of inadequate ships, equipment, or techniques.

Among these future study areas are: impact of mesoscale physical processes on biotic structure and dynamics and its seasonal variability; high resolution, long time-series studies of upper ocean biological dynamics in a given hydrographic province and its interannual variability; deep-sea studies of resident fauna; and nutrient and particulate fluxes into and out of surface waters.

The current trend of using microprocessor-automated equipment, expendable probes, and remote sensors (satellites, moorings, drifters) will accelerate. There will be an even greater need for clean, dry, stable spaces on ships for sophisticated analytical laboratory equipment. Work on board ships will be increasingly multidisciplinary and labor intensive, giving rise to a need for more laboratory and living accommodations for scientists and technicians.

E. Ocean Engineering. Academic activities in ocean engineering in the coming decade are expected to fall into three categories:

- Engineering to enhance ocean science;
- Environmental studies to guide use of the oceans and to establish factors which control design of systems; and
- Exploratory development of systems, devices, structures, and vehicles needed to use the ocean effectively.

Development of engineering understanding requires ability to carry or to tow large devices to sea, deploy moorings and arrays of sensors, and make detailed observations both in the water column and on the seafloor. Some work may require special vehicles (e.g., manned spar buoy laboratories) but much should be done from well-designed large general purpose research ships, presuming they have the necessary handling gear, load carrying, and station keeping capabilities.

IV. Funding and Operations Requirements

The preceding discussion leads directly to insight into requirements for ships of the future. We must have a mix which will include the ability to work far from normal operating bases, will accommodate large scientific parties for multidisciplinary work on site with collected materials, will support deep diving submersibles and unmanned seafloor work systems, and can support acoustic systems ranging from multichannel seismic to doppler profiling current meters.

In recognition of these needs, UNOLS, with NSF and Navy support, examined the developing science mission requirements for new oceanographic ships and provided a plan for research vessel replacement and construction (UNOLS Fleet Replacement Committee Report, 1986). Conceptual designs of large ships to meet the research requirements of the next 20 to 30 years are included in that report. Table G.1 is a summary of the required construction schedule.

TABLE G.1
SHIP CONSTRUCTION SCHEDULE

<u>Time Frame</u>	<u>Large</u>	<u>Intermediate</u>	<u>Small</u>
1985-1989	1 GP 1 GP+MCS Modernize 2*		
1990-1994	1 GP+MCS 1 GP+Ice		1 GP+Ice
1995-1999		2 GP	1 GP
2000-2004	1 GP+Sub	1 GP	2 GP
2005-2009	1 GP	3 GP	
2010-2014	2 GP*		2 GP
Total	8	6	6

* R/V MELVILLE and R/V KNORR

GP = General purpose oceanographic research vessel
MCS = Compressors for multichannel seismics capability
Ice = Hull strengthened for ice capability
Sub = Submersible handling capability

New large ships will be much more capable than their predecessors. They will be longer and wider. They will carry more scientists and have more laboratory space and scientific storage. They will be faster, with more efficient power plants and hulls, and their range and endurance will be longer. They will cost less to operate and significantly less per scientist day. Most importantly, they will allow scientific work in sea conditions that are beyond the capabilities of the present fleet. Table G.2 compares the present large-ship fleet with the new ships recommended in the UNOLS Report.

TABLE G.2
THE AVERAGE LARGE SHIP

	Present	Future	% Change
Number in Fleet	7	8	+14
Length Overall (ft.)	220	255	+14
Beam (ft.)	41	56	+37
Displacement (tons)	1,730	3,000	+73
Speed (knots)	10	15	+50
Range (nautical miles)	10,000	13,000	+30
Endurance (days)	40	53	+39
Crew	23	18	-22
Scientists	23	28 (43w/vans)	+22(+87)
Lab Space (sq.ft.)	1,300	4,000	+310
Deck Space (sq.ft.)	2,000	5,000	+250
Sci. Storage (cu.ft.)	4,200	16,250	+387
Days At Sea	270	270	0
Operational Cost (\$M)	\$2.8	\$2.6 *	-7
Daily Rate	\$10,370	\$9,630	-7
Scientist Days **	43,470	75,600	+174
Cost/Scientist Day	\$450	\$275	-39

* Assumptions: Constant Dollars;
Crew decreases by 22 %;
Fuel decreases by 15 % (efficient engines and hull);
Supplies increase by 20 % (in proportion to people); and
Other costs remain unchanged.

** 23 Scientists per day now; 35 in the future.

Six of the seven large ships in the present academic fleet were built and are owned by the U.S. Navy - *Conrad*, *Thompson*, *Washington*, *Knorr*, *Melville*, and *Moana Wave*. Present Navy plans for the late 1980's call for construction of two new large ships for academic research plus modernization of the *Knorr* and *Melville*. If realized, these plans should meet the UNOLS construction schedule for 1985-1989 and provide the research platforms needed for the late 1980's as the Global Ocean Studies and Ocean Lithosphere Studies initiatives are ramping up. The Navy has no plans for additional construction of academic research vessels beyond 1990.

The complementary NSF plan calls for engineering designs leading to construction of two large ships plus a smaller, ice-strengthened ship in the period 1990-94. The combination of Navy and NSF plans will result in construction of one small, ice-capable and four large ships between 1988 and 1995, and modernization of two others.

The UNOLS report provides estimates for new ship construction costs. This is summarized in Figure G.1 which shows that \$98M in inflated dollars will be needed for the three NSF-planned ships in the 1990-94 time period. An additional \$50M will be required in 1995-96 to address the late 1990's requirements to continue with a fully capable modern fleet. These funds will support two additional smaller ships for delivery in 1996 and 1997. Specific planning for these needs has not yet been completed. The UNOLS Fleet Improvement Committee will begin to examine these needs in 1987.

To meet the 1990's requirements for fully implemented Global Ocean and Lithosphere programs, the core academic fleet must be augmented with additional ships beyond the identified Navy and NSF replacement and modernization plans. The existing academic research fleet evolved to its present size based upon core program requirements. The existing research ships, coupled with the more capable and effective new construction/replacement ships, can absorb some of the increased field program requirements but clearly cannot meet all of them.

Analysis of the "at sea" science requirements in the 1990's (Table G.3) shows a shortfall of available research ship time, including the new construction, of 2.5 ship-years in 1989 increasing to 8.5 ship-years by 1991 and remaining at about 10.0 ship-years of time to 1996.

Several complementary activities and programs are planned to provide the facilities needed by these science programs. These include consideration of:

- Use of long-term commercial charters for multichannel seismic capabilities needed by the Ocean Lithosphere Studies;
- Increased use of research ships provided by international partners/collaborators in Global Ocean Studies;
- Incorporation of new institution-owned research ships in the core academic fleet;
- Development of cooperative-use arrangements with other Federal agencies which operate research ships; and
- Additional commercial charters for specific science project needs on a short-term basis.

Summary Table G.3 For Science Requirements

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Ship and Equipment Funds	27.2	29.4	28.1	31.2	37.6	50.6	62.6	74.7	86.1	94.7	103.2	110.8	119
Ship Years Needed	15.2	16.5	15.7	17.5	19	23.5	27.8	31.5	34.2	35.2	35.6	35.2	34.6
Ship Years Available	19	20	20	20	20	21	22	23	24	24	25	25	26
Surplus/Shortfall in Ship Years	3.8	3.5	4.3	2.5	1	-2.5	-5.8	-8.5	-10.2	-11.2	-10.6	-10.2	-8.6

In summary, to meet long-term oceanographic science needs, it is essential to implement during the 1990's a balanced program of new research ship construction and expanded international, interagency, institutional, and commercial charter arrangements. Funding requirements are presented in Table G of Section IV.

SECTION IV
BUDGETS

BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR THE NSF OCEAN SCIENCES DIVISION													
IV. Composite	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
CORE PROGRAM													
Ocean Sciences Research Support (OSRS)													
Physical Oceanography	15.50	15.90	15.00	16.90	17.90	19.25	21.18	23.29	25.62	28.18	31.00	34.10	37.51
Chemical Oceanography	11.80	12.40	11.70	12.10	12.30	13.31	14.64	16.11	17.72	19.49	21.44	23.58	25.94
Marine Geol & Geophysics	14.60	15.20	15.40	15.40	15.90	17.16	18.88	20.76	22.84	25.12	27.64	30.40	33.44
Biological Oceanography	12.80	13.90	13.40	13.40	14.40	15.40	16.94	18.63	20.50	22.55	24.80	27.28	30.01
Sub-total (OSRS)	54.70	57.40	55.50	57.80	60.50	65.12	71.64	78.79	86.68	95.34	104.88	115.36	126.90
Oceanographic Centers & Facilities Support (OCFS)													
Ship Operations	27.20	29.40	28.10	28.00	28.00	30.80	33.88	37.27	40.99	45.09	49.60	54.56	60.02
Ocean Technology	5.70	5.80	5.90	6.90	6.90	7.59	8.35	9.18	10.10	11.11	12.22	13.45	14.79
Ocean Drilling	26.30	26.70	28.90	30.10	31.30	33.35	35.54	37.90	40.43	43.16	46.09	49.24	52.64
Sub-total (OCFS)	59.20	61.90	62.90	65.00	66.20	71.74	77.77	84.35	91.52	99.36	107.91	117.25	127.45
SUBTOTAL FOR OCE CORE PROGRAMS	113.90	119.30	118.40	122.80	126.70	136.86	149.41	163.14	178.20	194.70	212.79	232.61	254.35
CRITICAL NEEDS													
Ocean Sciences Research Support (OSRS)													
Physical Oceanography						4.00	6.05	8.60	8.78	7.97	7.22	6.98	7.33
Chemical Oceanography						4.00	6.05	8.60	8.76	8.02	7.28	6.94	7.41
Marine Geology & Geophysics						5.00	7.10	9.71	9.92	9.23	8.55	8.28	9.61
Biological Oceanography					1.50	8.00	13.55	18.60	21.58	22.47	22.47	22.98	24.20
Sub-total (OSRS)					1.50	21.00	32.75	45.51	49.04	47.69	45.52	45.18	48.55
Oceanographic Centers & Facilities Support (OCFS)													
Ship Operations						2.70	3.11	3.63	3.95	4.17	4.38	4.60	4.83
Ocean Technology						3.50	4.20	5.00	5.45	6.01	6.31	6.62	6.95
Ocean Drilling						4.10	4.78	9.36	6.85	7.19	7.55	7.93	8.33
Sub-total (OCFS)						10.30	12.09	17.99	16.25	17.37	18.24	19.15	20.11
SUBTOTAL FOR OCE CRITICAL NEEDS					1.50	31.30	44.84	63.50	65.29	65.06	63.76	64.33	68.66

Long Range Plan Budget

IV. Composite (continued)

THE GLOBAL PROGRAM	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Global Ocean & Lithosphere Studies													
1a. Global Circulation, Climate and Productivity				8.10	13.22	25.31	39.16	48.22	50.98	51.80	50.76	48.63	49.33
1b. Open Ocean Fluxes				1.40	5.80	7.40	11.40	14.90	17.00	18.28	19.20	20.14	21.11
1c. Coastal Dynamics and Fluxes						2.00	4.00	8.00	14.00	20.00	24.00	25.20	26.44
1d. Ecosystems Dynamics and Recruitment						2.50	5.50	9.00	12.00	14.10	15.24	16.00	16.79
1e. Land/Sea Interface						1.00	1.60	2.80	4.00	5.00	6.00	6.30	6.61
2a. Continental Margins						2.00	4.00	8.00	12.00	15.00	16.00	16.80	17.64
2b. Ridgecrest Processes				1.00	1.70	4.70	9.20	12.20	14.90	15.85	16.64	17.47	18.35
3a. Ship Construction					0.60	4.00	10.00	20.00	20.00	22.00	22.00	25.00	25.00
3b. Ocean Technology *				0.40	0.80	4.00	8.00	11.00	12.40	13.82	15.26	15.72	16.21
3c. Ship Operations and Facilities *				3.24	9.58	19.76	28.74	37.42	45.12	49.58	53.58	56.22	59.05
SUBTOTAL FOR THE OCEGLOBAL PROGRAM				10.50	21.32	48.91	84.86	123.12	144.88	162.03	169.84	175.54	181.27
ODP INTERNATIONAL FUNDS	5.20	7.60	12.90	15.20	17.50	18.40	19.29	20.26	21.27	22.33	23.45	24.62	25.86
TOTAL OF OCE CORE PROGRAMS, CRITICAL NEEDS AND THE GLOBAL PROGRAM, EXCLUDING INTERNATIONAL FUNDS	113.90	119.30	118.40	133.30	149.52	217.07	279.11	349.76	388.37	421.79	446.39	472.48	504.28

* Note: In this and the following tables, the total costs of global programs are the sum of sub-programs 1a-e, 2a-b and 3a. The sub-programs of categories 1 and 2 contain the costs of 3b and 3c.

IV A BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR PHYSICAL OCEANOGRAPHY

CORE PROGRAM	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
A. Ocean Circulation	9.40	9.10	8.20	10.20	10.80	11.44	12.58	13.84	15.23	16.75	18.42	20.27	22.29
B. Coastal/Estuarine	2.40	2.80	2.70	2.80	2.80	3.08	3.39	3.73	4.10	4.51	4.96	5.46	6.00
C. Ocean/Atmosphere Coupling	1.50	1.60	1.60	1.60	1.70	1.87	2.06	2.26	2.49	2.74	3.01	3.31	3.64
D. Waves and Tides	0.80	0.90	1.00	1.00	1.00	1.10	1.21	1.33	1.46	1.61	1.77	1.95	2.14
E. Microstructure/Turbulence	1.40	1.50	1.50	1.50	1.60	1.76	1.94	2.13	2.34	2.58	2.83	3.12	3.43
Sub-total	15.50	15.90	15.00	17.10	17.90	19.25	21.18	23.29	25.62	28.18	31.00	34.10	37.51
CRITICAL NEEDS													
A. Technology Development						1.00	1.50	2.00	1.50	1.00	1.05	1.10	1.16
B. New Facilities						1.00	1.50	3.00	3.50	3.00	2.00	1.50	1.58
C. Facilities Improvement						1.00	2.00	2.50	2.63	2.76	2.89	3.04	3.19
D. Post-Doctoral Programs						1.00	1.05	1.10	1.16	1.22	1.28	1.34	1.41
Sub-total						4.00	6.05	8.60	8.78	7.97	7.22	6.98	7.33
THE GLOBAL PROGRAM													
1. GLOBAL OCEAN STUDIES	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
A. Climate, Circulation & Productivity													
(1) WOCE				3.00	6.90	12.00	20.00	24.00	26.00	27.30	28.70	30.00	31.60
(2) TOGA				3.00	4.50	5.50	7.00	9.00	11.00	11.00	9.00	6.50	5.00
(3) El Niño Rapid Response				0.60	1.10	0.70	2.50	3.50	3.50	2.50	1.50		
(4) Indo-US Monsoon Project				1.00	1.05	1.10	1.16	1.22	1.28	1.34	1.41	1.48	1.55
(5) Ocean Modelling				7.60	13.55	21.80	33.16	40.22	41.78	42.14	40.61	37.98	38.15
Sub-total				2.20	5.80	10.60	12.80	13.90	14.80	14.00	14.70	15.40	16.20
(ships/facilities/AMS only)													
B. Open Ocean Fluxes													
(ships/facilities only)													
C. Coastal Dynamics/Fluxes						0.50	1.00	2.00	3.50	5.00	6.00	6.30	6.60
(ships/facilities only)						0.19	0.38	0.75	1.31	1.88	2.25	2.36	2.48
D. Ecosystems Dynamics and Recruitment						0.50	1.00	1.50	2.00	2.10	2.21	2.32	2.43
(ships/facilities only)						0.19	0.38	0.56	0.75	0.79	0.83	0.87	0.91
E. Land/Sea Interface													
(ships/facilities only)													
2. OCEAN LITHOSPHERE STUDIES													
A. Continental Margins													
(ships/facilities only)													
B. Ridgecrest Processes													
(ships/facilities only)													
Sub-total Global Ocean Studies				7.60	13.55	22.80	35.16	43.72	47.28	49.24	48.81	46.59	47.18
(ships/facilities/centers only)				2.20	5.80	10.98	13.55	15.21	16.86	16.66	17.78	18.63	19.59
TOTAL PROGRAM	15.50	15.90	15.00	22.90	25.25	35.08	48.83	60.40	64.82	68.73	69.26	69.05	72.44

IV B BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR CHEMICAL OCEANOGRAPHY

CORE PROGRAM	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
A. Seawater Properties	0.80	0.60	0.50	0.50	0.50	0.55	0.61	0.67	0.73	0.81	0.89	0.97	1.07
B. Land/Sea Transfers	2.90	2.90	2.80	3.20	3.20	3.52	3.87	4.26	4.69	5.15	5.67	6.24	6.86
C. Ocean Fluxes	3.30	3.60	3.50	3.90	3.90	4.29	4.72	5.19	5.71	6.28	6.91	7.60	8.36
D. Biochemical Processes	1.40	1.40	1.20	1.40	1.50	1.54	1.69	1.86	2.05	2.25	2.48	2.73	3.00
E. Tracers	3.40	3.90	3.70	3.10	3.10	3.41	3.75	4.13	4.54	4.99	5.49	6.04	6.65
Sub-total	11.80	12.40	11.70	12.10	12.20	13.31	14.64	16.11	17.72	19.49	21.44	23.58	25.94
CRITICAL NEEDS													
A. Technology Development						1.00	1.50	2.00	1.50	1.00	1.10	1.10	1.20
B. New Facilities						1.00	1.50	3.00	3.50	3.00	2.00	1.50	1.60
C. Facilities Improvement						1.00	2.00	2.50	2.60	2.80	2.90	3.00	3.20
D. Post-Doctoral Programs						1.00	1.05	1.10	1.16	1.22	1.28	1.34	1.41
Sub-total						4.00	6.05	8.60	8.76	7.22	7.28	6.94	7.41

THE GLOBAL PROGRAM	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
1. GLOBAL OCEAN STUDIES													
A. Climate, Circulation & Productivity (WOCE) (ships/facilities only)				0.50	0.67	1.51	2.50	3.00	3.20	3.36	3.53	3.70	3.89
B. Open Ocean Fluxes (ships/facilities/AMS only)				0.19	0.25	0.57	0.94	1.13	1.20	1.26	1.32	1.39	1.46
C. Coastal Dynamics/Fluxes (ships/facilities only)				0.70	2.90	3.70	5.20	6.70	7.50	7.90	8.30	8.70	9.10
D. Ecosystems Dynamics and Recruitment (ships/facilities only)				0.30	1.50	1.80	2.40	3.00	3.10	3.26	3.42	3.59	3.77
E. Land/Sea Interface (ships/facilities only)						0.50	1.00	2.00	3.50	5.00	6.00	6.30	6.62
						0.19	0.38	0.75	1.31	1.88	2.25	2.36	2.48
								0.50	1.00	1.50	2.00	2.10	2.20
								0.19	0.38	0.56	0.75	0.79	0.83
						0.50	0.80	1.40	2.00	2.50	3.00	3.15	3.30
						0.19	0.30	0.53	0.75	0.94	1.13	1.18	1.24

2. OCEAN LITHOSPHERE STUDIES													
A. Continental Margins (ships/facilities only)						0.40	0.80	1.40	1.80	2.10	2.20	2.31	2.43
B. Ridgecrest Processes (ships/facilities only)						0.15	0.30	0.53	0.68	0.79	0.83	0.87	0.91
Sub-total- Global Ocean Studies (ships/facilities/centers only)				1.20	3.57	6.61	10.30	15.00	19.00	22.36	25.03	26.26	27.54
				0.49	1.75	2.74	4.01	5.59	6.74	7.89	8.87	9.31	9.77
TOTAL PROGRAM (excluding ships,facilities, and centers)	11.80	12.40	11.70	12.81	13.92	21.18	26.98	34.12	38.74	41.97	44.87	47.47	51.11

BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR BIOLOGICAL OCEANOGRAPHY

IV C

CORE PROGRAM

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
A. Primary Production	2.56	2.78	2.68	2.80	2.90	3.08	3.39	3.73	4.10	4.51	4.96	5.46	6.00
B. Microbial Loop	1.83	1.99	1.91	2.00	2.00	2.20	2.42	2.66	2.93	3.22	3.54	3.90	4.29
C. Higher Trophic Levels	2.93	3.18	3.06	3.20	3.50	3.52	3.87	4.26	4.69	5.15	5.67	6.24	6.86
D. Specialized Environments	1.65	1.79	1.72	1.80	1.90	1.98	2.18	2.40	2.64	2.90	3.19	3.51	3.86
E. Large Marine Ecosystems	3.84	4.17	4.02	4.20	4.20	4.62	5.08	5.59	6.15	6.76	7.44	8.18	9.00
Sub-total	12.80	13.90	13.40	14.00	14.50	15.40	16.94	18.63	20.50	22.55	24.80	27.28	30.01

CRITICAL NEEDS

A. Technology Development						2.00	4.00	5.00	5.30	5.50	5.80	6.10	6.40
B. New Facilities						1.00	1.50	3.00	3.50	3.00	2.00	1.50	1.60
C. Facilities Improvement						1.00	2.00	2.50	2.63	2.76	2.89	3.04	3.19
D. Post-Doctoral Programs						1.00	1.05	1.10	1.16	1.22	1.28	1.34	1.41
E. Biotechnology				1.50		3.00	5.00	7.00	9.00	10.00	10.50	11.00	11.60
Sub-total				1.50		8.00	13.55	18.60	21.58	22.47	22.47	22.98	24.20

THE GLOBAL PROGRAM

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
1. GLOBAL OCEAN STUDIES													
A. Climate, Circulation & Productivity (ships/facilities only)						2.00	3.50	5.00	6.00	6.30	6.62	6.95	7.29
B. Open Ocean Fluxes (ships/facilities/AMS only)				0.70	2.90	0.75	1.31	1.88	2.25	2.36	2.48	2.60	2.73
C. Coastal Dynamics/Fluxes (ships/facilities only)				0.26	1.50	1.80	2.40	3.00	3.10	3.26	3.42	3.59	3.77
D. Ecosystems Dynamics and Recruitment (ships/facilities only)						0.50	1.00	2.00	3.50	5.00	6.00	6.30	6.62
E. Land/Sea Interface (ships/facilities only)						0.19	0.38	0.75	1.31	1.88	2.25	2.36	2.48
						2.00	4.50	7.00	9.00	10.50	11.03	11.58	12.16
						0.75	1.69	2.63	3.38	3.94	4.13	4.34	4.56
						0.50	0.80	1.40	2.00	2.50	3.00	3.15	3.31

2. OCEAN LITHOSPHERE STUDIES

A. Continental Margins (ships/facilities only)				0.20	0.40	0.80	1.40	1.80	2.10	2.20	2.31	2.43	2.55
B. Ridgecrest Processes (ships/facilities only)				0.08	0.15	0.30	0.53	0.68	0.79	0.83	0.87	0.91	0.96
Sub-total- Global Ocean Studies (ships/facilities/centers only)				0.90	3.30	9.50	16.40	23.90	30.10	34.38	37.22	39.08	41.03
				0.34	1.65	3.79	6.30	8.93	10.83	12.26	13.15	13.81	14.50
TOTAL PROGRAM (excluding ships, facilities, & centers)	12.80	13.90	13.40	14.56	17.15	29.11	40.59	52.21	61.36	67.14	71.34	75.53	80.74

IV D BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR MARINE GEOLOGY AND GEOPHYSICS

CORE PROGRAM	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
A. Continental Margins	2.90	3.20	3.20	3.20	3.21	3.52	3.87	4.26	4.69	5.15	5.67	6.24	6.86
B. Oceanic Ridges & Basins	3.00	3.20	3.50	3.40	3.40	3.74	4.11	4.53	4.98	5.48	6.02	6.63	7.29
C. Geochemistry of Crust	3.00	3.00	3.00	3.00	3.20	3.30	3.63	3.99	4.39	4.83	5.31	5.85	6.43
D. Marine Sediments	2.50	2.60	2.40	2.60	2.60	2.86	3.15	3.46	3.81	4.19	4.61	5.07	5.57
E. Geologic & Climatic Hist.	3.20	3.20	3.30	3.40	3.40	3.74	4.11	4.53	4.98	5.48	6.02	6.63	7.29
Sub-total	14.60	15.20	15.40	15.60	15.90	17.16	18.88	20.76	22.84	25.12	27.64	30.40	33.44

CRITICAL NEEDS

A. Technology Development													
B. New Facilities													
C. Facilities Improvement													
D. Post-Doctoral Programs													
E. ODP Sample Analysis													
Sub-total						5.00	7.10	9.71	9.92	9.23	8.55	8.28	9.61

THE GLOBAL PROGRAM	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
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1. GLOBAL OCEAN STUDIES

A. Climate, Circulation & Productivity (ships/facilities only)													
B. Open Ocean Fluxes (ships/facilities only)								1.00	1.50	2.00	2.63	2.76	2.89
C. Coastal Dynamics/Fluxes (ships/facilities only)						0.50	1.00	2.00	3.50	5.00	6.00	6.30	6.60
D. Ecosystems Dynamics and Recruitment (ships/facilities only)						0.19	0.38	0.75	1.31	1.88	2.25	2.36	2.48
E. Land/Sea Interface (ships/facilities only)													

2. OCEAN LITHOSPHERE STUDIES

A. Continental Margins (ships/facilities only)						2.00	4.00	8.00	12.00	15.00	16.00	16.80	17.64
B. Ridgecrest Processes (ships/facilities only)				0.56	1.00	0.75	1.50	3.00	4.50	5.63	6.00	6.30	6.62
				0.21	0.38	1.31	2.63	3.38	4.13	4.33	4.55	4.78	5.01
Sub-total- Global Ocean Studies (ships/facilities/centers only)				0.56	1.00	6.00	13.00	20.50	28.50	34.05	36.75	38.59	40.50
				0.21	0.38	2.25	4.88	7.69	10.69	12.77	13.78	14.47	15.19

TOTAL PROGRAM	14.60	15.20	15.40	15.95	16.23	25.91	34.10	43.28	50.57	55.64	59.16	62.80	68.37
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IV E BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR OCEAN DRILLING

CORE PROGRAM

	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
A. International Operations	23.90	22.90	22.00	20.70	21.70	22.79	23.92	25.12	26.38	27.70	29.08	30.53	32.06
B. Science Support	2.40	3.80	6.90	9.40	9.60	10.56	11.62	12.78	14.06	15.46	17.01	18.71	20.58
Sub-total	26.30	26.70	28.90	30.10	31.30	33.35	35.54	37.90	40.43	43.16	46.09	49.24	52.64

CRITICAL NEEDS

A. Downhole Experiments						1.50	1.58	1.65	1.74	1.82	1.91	2.01	2.11
B. Regional Geophysics						2.00	2.10	2.21	2.32	2.43	2.55	2.68	2.81
C. Riser Drilling						0.60	1.10	5.50	2.80	2.94	3.09	3.24	3.40
Sub-total						4.10	4.78	9.36	6.85	7.19	7.55	7.93	8.33

**TOTAL PROGRAM (NSF)
INTERNATIONAL FUNDS**

	26.30	26.70	28.90	30.10	31.30	37.45	40.32	47.26	47.28	50.35	53.64	57.17	60.97
	5.20	7.60	12.90	15.20	17.50	18.40	19.29	20.26	21.27	22.33	23.45	24.62	25.86

TOTAL PROGRAM

	31.50	34.30	41.80	45.30	48.80	55.82	59.61	67.52	68.55	72.69	77.09	81.80	86.82
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IV F BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR OCEAN TECHNOLOGY

CORE PROGRAM

A. Ocean Instrumentation	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
B. Shipboard Technicians	2.20	1.80	1.70	1.90	1.90	2.09	2.30	2.53	2.78	3.06	3.37	3.70	4.07
C. Ocean Technology	2.30	2.40	2.50	2.70	2.70	2.97	3.27	3.59	3.95	4.35	4.78	5.26	5.79
	1.20	1.60	1.70	2.30	2.30	2.53	2.78	3.06	3.37	3.70	4.07	4.48	4.93
Sub-total	5.70	5.80	5.90	6.90	6.90	7.59	8.35	9.18	10.10	11.11	12.22	13.45	14.79

CRITICAL NEEDS

A. In Situ Measurements						1.50	1.70	2.00	2.30	2.70	2.84	2.98	3.13
B. Intelligent Systems						2.00	2.50	3.00	3.15	3.31	3.47	3.65	3.83
Sub-total				0.00	0.00	3.50	4.20	5.00	5.45	6.01	6.31	6.62	6.95

THE GLOBAL PROGRAM

A. Remote Measurements	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
B. Sample Collecting Systems				0.20	0.40	1.50	3.00	4.00	4.20	4.41	4.63	4.86	5.11
C. Ocean Structures				0.20	0.40	1.50	3.00	4.00	4.20	4.41	4.63	4.86	5.11
						1.00	2.00	3.00	4.00	5.00	6.00	6.00	6.00
Sub-total				0.40	0.80	4.00	8.00	11.00	12.40	13.82	15.26	15.72	16.21

TOTAL PROGRAM

	5.70	5.80	5.90	7.30	7.70	15.09	20.55	25.18	27.95	30.94	33.79	35.79	37.96
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BUDGETARY IMPLICATIONS OF THE LONG RANGE PLAN FOR SHIP OPERATIONS													
IV G	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
CORE PROGRAM													
A. Ship Operations	25.30	27.10	26.40	26.00	26.00	28.60	31.46	34.61	38.07	41.87	46.06	50.67	55.73
B. Ship Equipment	1.90	1.70	1.50	1.60	1.60	1.76	1.94	2.13	2.34	2.58	2.83	3.12	3.43
C. Construction/Conversion		0.60	0.20	0.40	0.40	0.44	0.48	0.53	0.59	0.64	0.71	0.78	0.86
Sub-total	27.20	29.40	28.10	28.00	28.00	30.80	33.88	37.27	40.99	45.09	49.60	54.56	60.02
CRITICAL NEEDS													
A. Scientific Equipment						0.50	0.80	1.20	1.40	1.50	1.58	1.65	1.74
B. Ship Modernization						2.20	2.31	2.43	2.55	2.67	2.81	2.95	3.10
Sub-total						2.70	3.11	3.63	3.95	4.17	4.38	4.60	4.83
THE GLOBAL PROGRAM													
A. Ship Construction	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
B. Ship Operations & Equipment (included in science budgets)					0.60	4.00	10.00	20.00	20.00	22.00	22.00	25.00	25.00
TOTAL PROGRAM	27.20	29.40	28.10	28.00	28.60	37.50	46.99	60.89	64.94	71.27	75.99	84.17	89.00