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# Global Change: A Biogeochemical Perspective

Workshop Chairman

**Michael McElroy**  
Harvard University

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## Abstract

This report describes a research program that is designed to enhance our understanding of the earth as the support system for life. The program will study change, both natural and anthropogenic, that might affect the habitability of the planet on a time scale roughly equal to that of a human life. On this time scale the atmosphere, biosphere, and upper ocean must be treated as a single coupled system. The program therefore focuses attention on the need for understanding the processes affecting the distribution of essential nutrients – carbon, nitrogen, phosphorous, sulfur, and water – within this coupled system. The importance of subtle interactions among chemical, biological, and physical effects is emphasized. The specific objectives of the program are to define the present state of the planetary life-support system; to elucidate the underlying physical, chemical, and biological controls; and to provide the body of knowledge required to assess changes that might impact the future habitability of the earth.

## Preface

This study builds upon the principles described in *Global Change: Impacts on Habitability* (JPL D-95, 1982). That document stressed the importance of changes in the biogeochemical cycles of water, plant nutrients and toxins. To understand these cycles requires detailed studies of the chemistry, physics and biology of the atmosphere, the oceans and the land surface, considered both individually and as a single interacting system.

It is, regrettably, too easy to become diffuse and ineffective in approaching such a complex objective. A directed program requiring large resources and promising results in an acceptable period of time must be broken down into elements for which specific studies can be made and from which specific answers can be sought. The most promising way to accomplish this task is to define with care the issues relating to chemical cycles and to then identify the physical, chemical and biological research required to allow significant progress. That definition is the purpose of this paper.

We have tried to indicate the questions which must be answered in order to predict the chemical consequences of change due both to natural causes and human activity. We feel some confidence in the definition of problems in the chemical and biological areas. The physical problems, concerned principally with the transport of heat and chemical species by the oceans and the atmosphere, are scarcely mentioned in this document. This imbalance may be attributed to the fact that many of the physical problems involved have been given careful consideration already under the aegis of the World Climate Program, and considerable documentation already exists. The task is one of reconciliation rather than innovation and will be addressed in a separate document.

A comment should be made as to the length and the size of the program described here. If we are to address problems involving the 5-50 year time scale, the time to establish necessary data sets cannot be much shorter. We are proposing a program to be carried out over decades, although it may be phased in such a way as to complete some studies before others.

The observations will be global and the satellite one of the principal tools. The complexity of payloads will not be as great as required for the exploration of Venus and Mars but the number will be much greater. The size of the program will bear some resemblance to the scale of the NASA planetary program during the past two decades. The interdisciplinary nature of the science program required for research on global habitability will have many aspects in common with planetary exploration. We propose a planetary program with the earth as its focus. The lessons of planetary exploration can be put to good use in this new context, and the experience gained may lead us to better ideas for effective continuing exploration of the entire solar system.

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Michael McElroy, Harvard University, chairman  
Wesley Huntress, Jet Propulsion Laboratory, executive officer  
Robert Watson, NASA representative

Berrien Moon., University of New Hampshire  
Ronald Prinn, Massachusetts Institute of Technology  
Richard Goody, Harvard University  
Fanny Knox, Harvard University  
James McCarthy, Harvard University  
Steven Wofsy, Harvard University



# Global Change: A Biogeochemical Perspective

## I. General Considerations

This document presents the outline of a research program designed to improve our understanding of the biosphere, ocean and atmosphere as a coupled system, with an overall objective to develop the base of knowledge necessary to allow prediction of long term (5-100 year) changes which may affect the habitability of the earth. It builds on general principles defined by *Global Change: Impacts on Habitability* (JPL D-95, 1982) and seeks to elaborate the scientific rationale for concepts enunciated in Vienna at Unispace 82.

*The program focuses on major biogeochemical cycles (C, N, P, S, H<sub>2</sub>O), and on the range of factors judged important for the global life support system (radiation and the quality of air, soil, and water). Man's influence on biogeochemical cycles is apparent and widely recognized. Perturbations to the carbon cycle are manifest through readily observable changes in the concentrations of atmospheric CO<sub>2</sub> and perhaps CH<sub>4</sub>. Likewise, perturbations to the nitrogen cycle are evidenced by changes in the concentrations of atmospheric N<sub>2</sub>O and other oxides of nitrogen. Increased mobilization of sulfur leads to enhanced concentrations of sulfate in precipitation and to an additional burden of sulfate aerosol in arctic haze, and it is difficult to identify a major river or estuary which has not been affected by the addition of phosphate from agricultural, urban or industrial sources. The human race has been eminently successful, applying technology to increase the production of food, providing, in part, the needs of a growing population. It has done so by altering natural and traditional patterns of land and water use, by deploying quantities of energy extracted for the most part from fossil fuel, and by congregat-*

ing people and wastes with increasing density. As noted in *Global Change: Impacts on Habitability*, we have reached the point of affecting the global system significantly within a few decades, while our ability to introduce countermeasures is on the same time scale or longer. We must take steps now to develop the body of knowledge required to permit wise policy choices for the future.

We envisage a program of research with the atmosphere, ocean, and land viewed as a single coupled system for the most part, and with separate systems receiving emphasis where necessary.

Our understanding of the stratosphere is relatively mature and priorities are readily defined. There is a continuing need to describe the function of the stratosphere as a coupled physical-chemical system. *The primary goal for stratospheric research is to understand the processes which regulate the distribution and abundance of O<sub>3</sub>, in order to assess the impact of man, not only as it may affect transmission of ultraviolet radiation to the earth's surface, but also as it may influence regional and global climate.*

*There are five major goals for tropospheric research: to understand the principal components of the hydrological cycle; to define the processes which regulate the distribution and abundance of lower atmospheric oxidants, notably O<sub>3</sub>, SO<sub>2</sub>, and NO<sub>2</sub>; to define factors which influence the chemistry of deposition, both dry and moist; to identify processes which affect the abundance of aerosols and of gases such as CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>, NH<sub>3</sub>, H<sub>2</sub>O; and to assess the impact of*

*anthropogenic infrared absorbers on the radiative budget of the atmosphere and on climate.*

Ozone in the troposphere plays an important role in the planetary life support system. It affects the penetration of ultraviolet sunlight and is a factor also in biospheric productivity. There is evidence that the yield of agricultural systems is reduced significantly at high ambient levels of tropospheric  $O_3$ . We need observational data and associated laboratory and theoretical analyses to define the extent of the human influence on the global distribution of tropospheric  $O_3$  and other oxidants, recognizing the importance of this objective to the overall goals of the habitability program.

The goals for stratospheric and tropospheric research are not unrelated. Chemical processes in the troposphere significantly influence the supply of gases to the stratosphere. Methyl chloride, for example, is thought to provide the largest source of chlorine in the unperturbed stratosphere. The quantity of  $CH_3Cl$  reaching the stratosphere is regulated by reactions involving OH in the troposphere. Similar processes regulate the flux of  $CH_4$  to the stratosphere. The stratosphere provides an important source of tropospheric  $O_3$ . Ozone is both produced and consumed in the troposphere. The relative importance of sources and sinks are modulated, it is thought, by the ambient level of  $NO_x$ .

The radical OH plays a central role in the removal of tropospheric gases such as  $SO_2$ ,  $H_2S$ ,  $CH_3Cl$ ,  $CH_3CCl_3$ , CO,  $CH_4$ , and other hydrocarbons. We see an urgent need for instrument development, and for field, laboratory, and theoretical studies to define the chemical processes which determine the abundance and distribution of OH in the troposphere. Information on OH, in combination with measurements defining the distribution of short-lived C-, N-, and S-bearing gases ( $CO$ ,  $CH_4$ , other hydrocarbons,  $NH_3$ ,  $NO_x$ ,  $H_2S$ , COS,  $CS_2$ ,  $(CH_3)_2S$ , etc.) can provide valuable clues to the function of the major biogeochemical cycles, contributing significantly to all four objectives stated earlier for the troposphere.

The carbon cycle merits special attention. The carbon cycle is not in a steady state—the level of atmospheric  $CO_2$  has increased steadily since careful measurements began in 1958, by as much as 25% since 1850. The transient behavior of  $CO_2$  provides a unique opportunity to gain insight into the function of the global carbon cycle, through which to develop a deeper appreciation for the function of the biosphere as an integrated planetary system. The change observed in  $CO_2$  results from a combination of influences: release of  $CO_2$  associated with combustion of fossil and biospheric carbon; possible alteration of carbon stored by the biosphere; possible modification of carbon stored in soils and sediments; and a probable change in the rate at which carbon is taken up by

the ocean. The concentration of atmospheric  $CO_2$  is expected to double by the early part of the next century. Carbon dioxide along with  $H_2O$  provides an efficient trap for infrared radiation emitted by the earth's surface and models suggest that doubling  $CO_2$  could lead to an increase in global mean temperature of as much as 2–3°C. Enhanced levels of  $CO_2$  could stimulate higher biospheric productivity and might be expected to impact the hydrological cycle, inducing closure of leaf stomata, leading to enhanced preservation of plant and soil moisture. *An important goal is to develop an understanding of the processes regulating change in  $CO_2$  today, to understand its evolution in the recent past, and to predict its future.* To succeed in this goal, we need to evolve a better understanding for the intrinsic and extrinsic factors influencing uptake and release of carbon by the biosphere, with a comparable improvement in our understanding of the role of the ocean. As a step towards this goal we should set *an immediate objective to define the content of carbon in various compartments of the present system—biosphere, soils, atmosphere, ocean, and sediments—and to establish measurement strategies to provide early indications of possible change.*

We need to specify accurately the extent of major terrestrial ecosystems (tropical forests, savanna, cropland, etc.) and to monitor these systems for change over an extended period. An initial goal would be to estimate as accurately as possible (ideally to within a few percent) quantities of carbon stored by the terrestrial biosphere and soils, and to identify factors which lead to change in the storage capacity of these reservoirs. Studies of perturbed systems, regions of major land clearance for example, may be particularly instructive in this regard. The major questions which need to be addressed are: To what extent is the storage capacity for carbon influenced by changes in the input of other nutrients, N, P, and S for example, by changing levels of atmospheric oxidant, by deposition of acidic sulfates and nitrates, by mobilization of metals, or by changes in local climate? How do changes in the biota feed back to modify the chemistry of air and water, or climate? What factors regulate the apportionment of carbon between living and dead components of terrestrial ecosystems and how might this division be affected either directly or indirectly by human activity? We see the need for an extensive program of remote sensing, in combination with intensive studies of selected systems, to address these issues. Observational programs must be complemented by appropriate theoretical and laboratory investigations. Studies of the biota are by their nature complex, requiring an interdisciplinary approach, with cooperation between physical and biological scientists essential if we are to make serious progress.

Investigation of a perturbed tropical ecosystem provides a case in point. We see the need for in situ atmospheric and aquatic measurements to define the input and removal of

chemical species from a selected study area with an appropriate control. We see a requirement for in situ investigations to identify the nature of relevant internal biological processes, with remote sensing employed to place the local investigation in context, permitting extrapolation to larger scale. Investigation of tropical systems could be imbedded thus in a larger matrix of studies designed to improve our understanding of the overall metabolism of the biosphere.

Studies of rivers can play a central role in the land-oriented portion of the habitability program. Rivers provide a convenient means to integrate the chemistry and biology of large areas of land—the Amazon drains approximately 30% of the South American continent. Rivers also provide a natural link between the land and ocean, exercising an important influence on the physical and chemical condition of coastal ecosystems. Changes in river chemistry, either in time or location, can alert us to changes in the land-based biosphere. *The primary goals of riverine research are: to determine the fluxes of water, C, N, P, and sediment from land to ocean, and to elucidate the factors controlling these fluxes.*

Coastal zones are significant since they provide the bulk of the world's harvest of fish. Coastal sediments offer a potential sink for carbon. Coastal wetlands can provide important sources for atmospheric gases such as  $\text{CH}_4$ ,  $\text{H}_2\text{S}$ , and  $(\text{CH}_3)_2\text{S}$  and the coastal environment is thought also to play a significant role in production of halocarbons such as  $\text{CH}_3\text{Cl}$ . The habitability program should emphasize coastal systems, recognizing their potential importance as a sink for carbon, their role as a source for harvestable protein, and as a source for various important atmospheric gases. *The research goal for coastal systems should focus on improving our understanding of processes as they affect coastal marine productivity and as they influence transfer of important chemical species from land to open ocean.*

*The general research goal for the oceans in global habitability is to quantify the role of the ocean in the biogeochemical cycles of C, N, P, and S, and to understand the role of the oceans in climate.* It is particularly important to determine the mechanisms for primary production, nitrogen fixation, denitrification, and the burial of organic debris. The coupling of physical and chemical processes across the atmosphere-ocean boundary, and across the thermocline, influences the availability of nutrients and affects the rate of photosynthesis in the upper mixed layer.

There is evidence that changes in oceanic productivity may have played a role in past fluctuations of climate. The abundance of carbon dioxide in the atmosphere appears to have varied by up to a factor of two over the past twenty thousand

years, with levels particularly low at the time of the Wisconsin glaciation. Changes in  $\text{CO}_2$  of this magnitude require significant transfer of carbon across the air-sea interface. The exchange of carbon between the atmosphere and ocean is influenced by sea state and by processes associated with the exchange of water between the upper and lower ocean. It may be influenced also by physiological changes in phytoplankton which might alter their requirements for nitrogen and phosphorous. On long time scales, the budgets of oceanic nitrogen and phosphorous are regulated by supply from the land and loss to sediments, with, in the case of nitrogen, contributions from in situ fixation, denitrification, and input from the atmosphere. On short time scales, productivity is influenced primarily by the transfer of nutrients across the thermocline.

Our knowledge of oceanic processes involved in global biogeochemical cycles is derived largely from ship-based data. The information required to extend this knowledge to the global scale is not yet available. For example, the rate for fixation of carbon by the oceans is uncertain by at least a factor of two. Fortunately, satellite technology has advanced to the point where it is possible to develop a global perspective on the circulation of the ocean, on the interaction of the oceans with the atmosphere, and on the response of marine biota to changes in the physics and chemistry of their environment. Satellite data can be used to examine ocean plankton distribution and productivity, and in conjunction with ship-board experiments can be employed to markedly improve our understanding of the ocean as a coupled physical, chemical and biological system.

The habitability program is intended to focus on changes which may take place on time scales of up to 100 years. It is clear that the task to assemble the base of knowledge prerequisite for comprehensive analysis is extraordinarily complex. It requires major advances in our understanding of the biosphere-atmosphere-ocean as a coupled system. The record of past chemical regimes preserved in sediments and ice cores may be particularly helpful as a stimulus to creative research. We must be prepared to make full use of these data, in addition to current observations, to the extent that they may contribute to our overall objectives. The record on past levels of  $\text{CO}_2$  and  $\text{CH}_4$  from studies of ice cores is notably important. Our success in accounting for these data can provide an important measure of our ability to forecast the future.

The overall dimensions of the habitability program are large. Individual elements—studies of the biota for example—can provide a challenge to the scientific community greater than that posed by a mission to another planet, the Viking mission to Mars for example. We believe that management experience gained during the 60's and 70's in planetary explor-

ation can be profitably applied in the 80's and 90's to coordinate studies of the earth as a coupled system. Existing programs, the Upper Atmosphere Research Program for example, and proposed missions such as UARS and TOPEX can contribute in important ways to the overall objectives of global habitability. The ultimate significance of global habitability lies in its emphasis on the atmosphere, ocean, and biosphere as a coupled system. The whole is more important, and indeed more challenging than the sum of its parts. Coordination of individual program elements is essential to allow rapid dissemination of relevant data, to facilitate integration of results obtained by other national and international bodies, to encourage real-time collegial discussions of research directions and options, and to focus theoretical and laboratory studies toward questions raised by the field studies addressing the ultimate objectives of the program.

The habitability program can provide a unifying theme for NASA's Earth Science Program, offering a series of challenges expected to occupy the Agency's attention for a decade or more. Successful and effective implementation of the program requires that NASA engage the expertise of a number of other government agencies, notably NOAA, DOE, EPA, Agriculture and Interior, and that it coordinate its mission with programs of the NSF. It requires the commitment of scientists from a variety of disciplines--biology, ecology, meteorology and oceanography to name a few--and presupposes arrangements encouraging scientists to work cooperatively to address the range of complex issues posed by the habitability concept. The program is global in scale, will involve both remote and in situ measurements, and should be coordinated with complementary efforts which exist already under the aegis of international bodies such as WMO, UNEP, and ICSU.

## II. Biogeochemical Cycles

The elements carbon, nitrogen, phosphorous, and sulfur are of special interest in the study of life on this planet. Along with water and sunlight, these elements are the essential components of living systems. The growth and decay of living organisms depends on exchange and transformation of these elements. We can begin to understand how the biosphere works by following the transformations that make up the biogeochemical cycle of individual elements. The need for such investigations has become apparent as evidence has accumulated indicating anthropogenic perturbation of the chemical, physical, and biological state of the atmosphere, land, and ocean. The magnitude of the perturbations is significant, and yet we have only a primitive understanding of the causes and potential significance of changes to global biogeochemical cycles.

To understand and predict the impact of man on global systems, we must determine the magnitudes of important fluxes and elucidate major processes in key ecosystems. For example, observations of  $\text{CH}_4$  have established that the atmospheric concentration is increasing, and hence that there is an imbalance between sources and sinks for the gas. We cannot predict the future evolution of  $\text{CH}_4$  with confidence until we define accurate rates for production and consumption in important systems, and until we can pinpoint factors responsible for the observed increase.

This chapter briefly reviews present knowledge of biogeochemical cycles for C, N, P, S and water. The discussion follows the traditional approach in which major global reservoirs are designated and cycles are represented by fluxes between these reservoirs. The treatment is necessarily somewhat artificial. Reservoirs are invariably diverse environments, neither homogeneous nor well-mixed, and the reservoir sizes are estimated by extrapolation from very small data sets. The response of the global system to human activities may be expected to be complex, reflecting the rich diversity of the terrestrial system. However, constructing these cycles provides a starting point to identify major processes and to reveal areas where our understanding should be improved. We begin with a discussion of carbon.

### The Carbon Cycle

Figure 1 shows a diagram of the global carbon cycle, using values representing the present, perturbed system. The pre-industrial atmospheric concentration of  $\text{CO}_2$  was 295 ppm ( $629 \times 10^{15}$  gC) or less. The concentration has increased to 338 ppm ( $720 \times 10^{15}$  gC) today due largely, we believe, to human influence, and continues to increase at a rate of about  $1 \text{ ppm yr}^{-1}$  ( $2 \times 10^{15}$  gC  $\text{yr}^{-1}$ ). The specific human influ-

ences involved are the burning of fossil fuels and alteration of the carbon content of the terrestrial biosphere. For comparison, photosynthesis and respiration create an annual oscillation in atmospheric  $\text{CO}_2$  in the range of  $5 \text{ ppm yr}^{-1}$  or  $11 \times 10^{15}$  gC  $\text{yr}^{-1}$ . The anthropogenic input is imposed on a large natural cycle, which is not fully understood. We cannot at present fully account for the excess  $\text{CO}_2$  added to the atmosphere. The budget of anthropogenic  $\text{CO}_2$  in the atmosphere is:

Input ( $10^{15}$ gC $\text{yr}^{-1}$ )		Uptake ( $10^{15}$ gC $\text{yr}^{-1}$ )	
Fossil fuel	6	Atmospheric increase:	3
Deforestation		Oceanic uptake:	2-3
minus regrowth:	1-3	Fertilization effects:	?
	<hr/> 7-9		<hr/> 5.6 + ?

This budget is unbalanced unless there is enhanced uptake due to effects of fertilization so that uptake by fertilization equals input by deforestation minus regrowth, or there is another sink, or the oceanic uptake is grossly underestimated, or the biospheric source is trivial (i.e., deforestation minus regrowth is zero). Carbon dioxide is essential to photosynthetic plants, and there is evidence that plants grow better at higher  $\text{CO}_2$  concentrations. However,  $\text{CO}_2$  is seldom the limiting factor for growth, and the magnitude of this effect is uncertain.

An additional sink suggested recently involves coastal sediments, which might be accumulating carbon from disturbed soils and from organic material fertilized by sewage nitrogen and phosphate. More investigation is needed to assess the potential of this and other possible sinks for anthropogenic carbon.

The ocean is the largest active reservoir for carbon. Exchange of carbon between the ocean and atmosphere is governed by physical, chemical, and biological processes. Only a small fraction of the total inorganic carbon dissolved in the ocean is present as  $\text{CO}_2$  gas (mole fraction  $\sim 0.5\%$ ); bicarbonate ion ( $\text{HCO}_3^-$ ) dominates (90%) and carbonate ion ( $\text{CO}_3^{2-}$ ) accounts for slightly less than 10% of the total. The marine biomass is small compared to the land biomass, consisting of only  $3 \times 10^{15}$  gC, or just over 0.5% of the carbon stored in terrestrial vegetation. On the other hand, total primary production in the oceans is  $20-45 \times 10^{15}$  gC  $\text{yr}^{-1}$  or larger, which makes it comparable to most estimates for primary production in terrestrial systems. Photosynthetic carbon is removed from the surface ocean by sinking of particulate organic carbon (POC) at a rate estimated to account for less than 10% of surface production.

On decadal time scales, turbulent mixing and downwelling of surface waters in polar regions create a sink for  $\text{CO}_2$  at high latitudes. Upwelling at low latitudes provides a compensating source. Estimates for the magnitude of the net meridional exchange are as high as  $30 \text{ ppm yr}^{-1}$ , or  $64 \times 10^{15} \text{ gC yr}^{-1}$ . Comparison of individual cold and warm oceanic zones reflects differences in  $\text{CO}_2$  partial pressures as high as 200 ppm. It is possible that improved understanding of the processes controlling the exchange of carbon between the atmosphere and ocean could lead to a revision in the magnitude of the oceanic uptake sufficient to balance the anthropogenic carbon.

The net release of  $\text{CO}_2$  to the atmosphere associated with deforestation is difficult to assess. Estimates for the amount of carbon in living organic matter on land vary between  $450\text{--}900 \times 10^{15} \text{ gC}$ , but the true uncertainty is probably larger than a factor of 2. Similar uncertainty is associated with estimates of rates for primary production, respiration, and for decay of detritus. The data base is very scant. The method of scaling up from selected sites is far from rigorous and large uncertainties exist concerning the geographic extent of different systems.

Soils provide a major reservoir for carbon. Accurate data on the size and activity of this pool are almost wholly lacking. Estimates range from  $700 \times 10^{15} \text{ gC}$  to  $1800 \times 10^{15}$ . The value in Figure 1 reflects recent human disturbance and revised data for the spatial extent of various ecological systems, but excludes slower turnover pools of carbon in deep humus and peat. The problem of determining how changes in land use have altered the release of carbon from terrestrial

biota and soils has two dimensions: determining the rate of change in land use and determining the response of the land to disturbance. It is surprising that even today estimates for the rate at which closed canopy tropical forests are removed for agriculture vary from  $3.5 \times 10^4 \text{ km}^2 \text{ yr}^{-1}$  to  $15 \times 10^4 \text{ km}^2 \text{ yr}^{-1}$ , and historical data on land use are even more uncertain. Improvement in estimates of biotic response requires much better measurements of primary production and carbon stocks.

In summary, uncertainties in our understanding of the carbon cycle lead to serious difficulties in balancing the current budget of atmospheric  $\text{CO}_2$ . There are a number of questions which must be addressed. How much carbon is contained in the terrestrial biosphere? What are the extent and carbon content of major terrestrial ecosystems? What factors control the internal routes for uptake and release of carbon? What are the key processes which control the exchange of carbon between the atmosphere and ocean? What is the response of the carbon cycle to human perturbations?

### The Nitrogen Cycle

A traditional view of the nitrogen cycle is presented in Figure 2. The principal classes of N compounds are shown in Figure 3. Most of terrestrial nitrogen is present as molecular  $\text{N}_2$ , which is chemically inert due to the strength of the  $\text{N} \equiv \text{N}$  bond. Processes which break the  $\text{N} \equiv \text{N}$  bond (nitrogen fixation) are relatively slow, amounting to less than  $0.2 \times 10^{15} \text{ gN yr}^{-1}$ . Nitrogen occurring in compounds as single atoms ("fixed nitrogen") is chemically versatile, with a wide

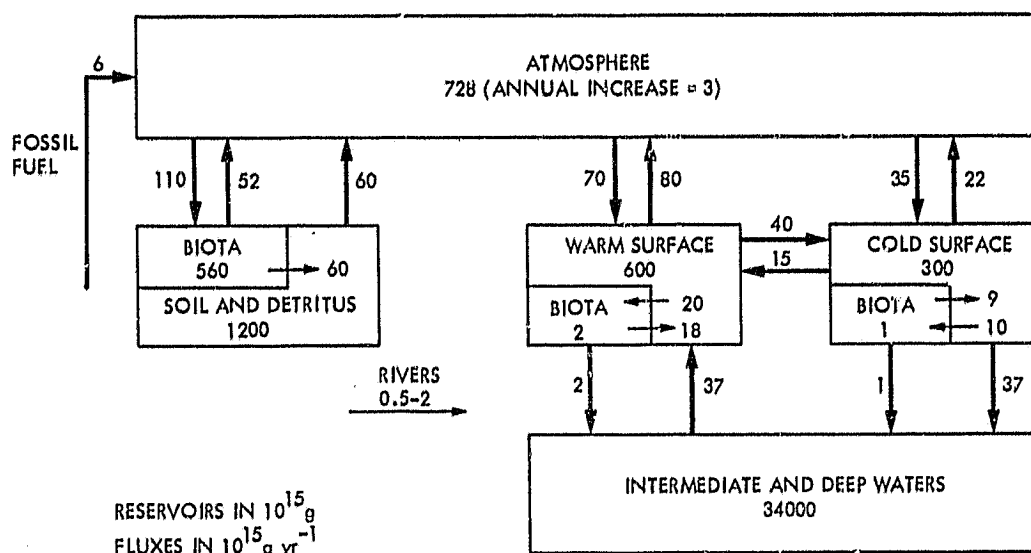


Fig. 1. Global carbon cycle

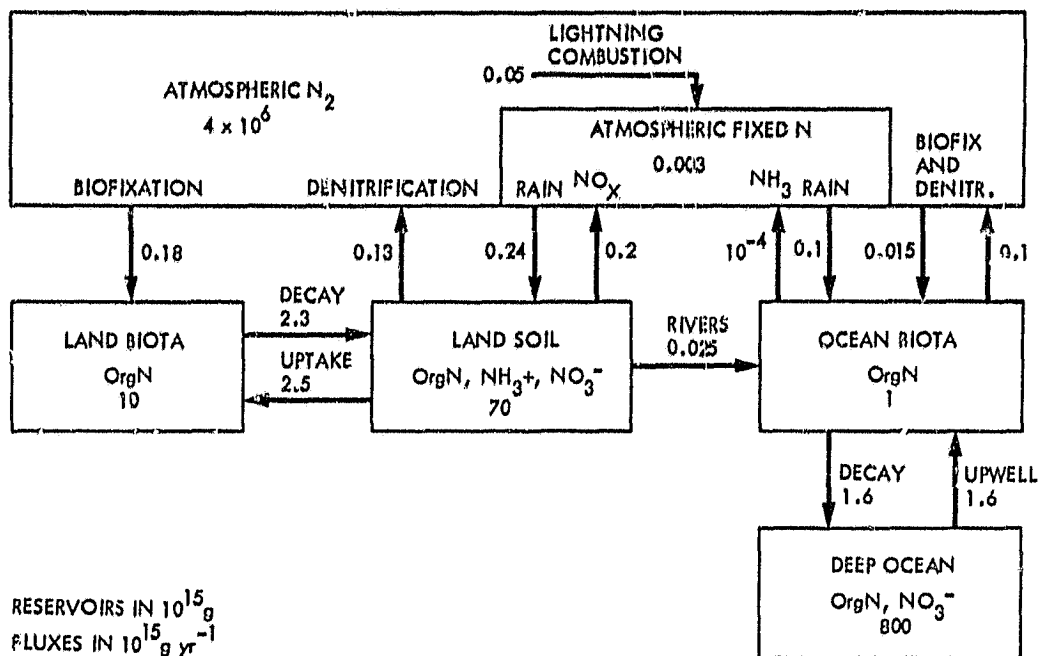


Fig. 2. Global nitrogen cycle

range of oxidation states from  $-3$  to  $+6$  (see Figs. 3-4). Recombination of fixed nitrogen is also slow, due largely to the kinetic stability of dissolved ions ( $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ) in solution. The recombination reaction is carried out biologically by bacteria using  $\text{NO}_3^-$  and  $\text{NO}_2^-$  as electron acceptors ("denitrification"). Denitrification takes place in anoxic, organic-rich locations such as flooded soils and sediments and anoxic waters of the major coastal upwelling systems.

Denitrification is essential to preservation of atmospheric  $\text{N}_2$ . In the absence of biological processes, the atmospheric nitrogen cycle would be open (Fig. 3), leading to accumulation of  $\text{NO}_2^-$  and  $\text{NO}_3^-$  in the oceans. There is no indication of such accumulation over geologic time, but it is unclear how the global system acts to establish balance between fixation and denitrification. Direct mechanisms coupling nitrogen fixation to denitrification have not been identified, and indirect connections are not obvious.

Nitrogen is cycled through the biosphere at rates 10-100 times as large as the rate for fixation of  $\text{N}_2$ . Mineral nitrogen ( $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ) is assimilated into terrestrial biomass at a rate of about  $2.5 \times 10^{15} \text{ gN yr}^{-1}$ , but this influx is balanced by decay of organic material ("mineralization"). The throughput of nitrogen in the oceans is roughly  $1.5 \times 10^{15} \text{ gN yr}^{-1}$  with a large uncertainty. The internal cycles of mineral nitrogen are essential links in the life-support system of the planet.

Human beings have a major impact on the global nitrogen cycle, with anthropogenic dominance at northern midlatitudes. Modern agricultural production requires a large input of nitrogen, provided in part by fixation associated with the manufacture of chemical fertilizer ( $0.05 \times 10^{15} \text{ gN yr}^{-1}$ ) and in part by nitrogen-fixing crops such as soybeans ( $0.10 \times 10^{15} \text{ gN yr}^{-1}$ ). Production of fixed nitrogen by these means is roughly comparable to natural rates at which nitrogen is fixed by plants and lightning (Fig. 3). Fixed nitrogen in the form of  $\text{N}_2\text{O}$  is added to the atmosphere today at a rate leading to an increase in concentration of 0.2% per year. Cultivation of soil serves to speed up rates for mineralization of organic nitrogen, with enhanced loss due to erosion and leaching. Unfortunately, there are few convincing studies defining quantitative rates and controlling variables for nitrogen transformations, either for agricultural ecosystems or for undisturbed biomes. Systematic studies are required if we are to assess present and future impacts of agriculture on the budgets and transformation of nitrogen in soils, waters, and the atmosphere.

Combustion processes (fossil fuels, forest fires) release 0.02 to  $0.04 \times 10^{15} \text{ gN yr}^{-1}$  as  $\text{NO}$  to the atmosphere, with sources concentrated in the northern hemisphere. This nitrogen could have an important impact on atmospheric chemistry, biological productivity, and on the chemistry of precipitation. Here again the observational basis for assessment of potential effects is unsatisfactory. There have been, however, a number

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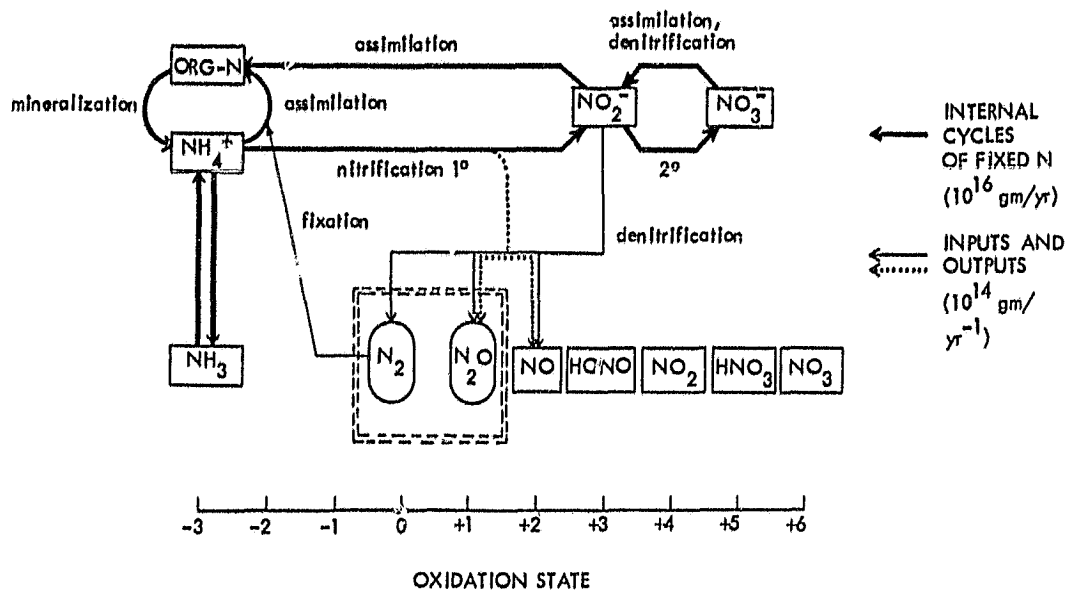


Fig. 3. Biological transformations of nitrogen

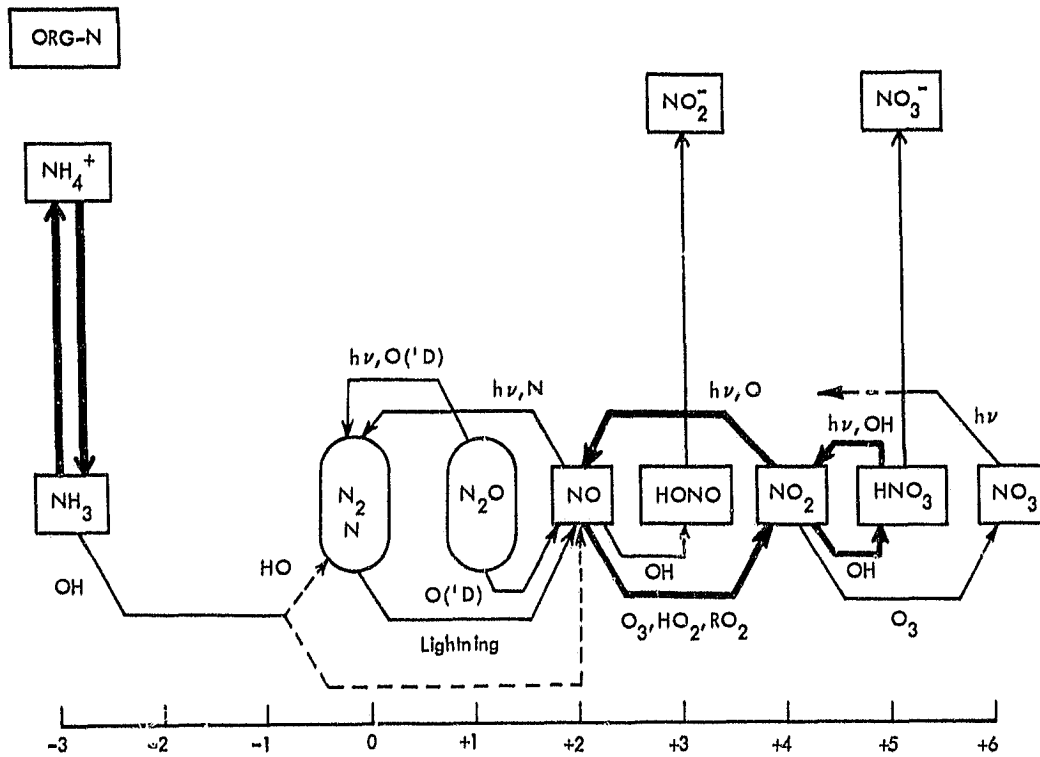


Fig. 4. Atmospheric transformations of nitrogen



of positive developments in the last 10 years. The experimental and theoretical base has expanded enormously over this time, allowing us to pose basic questions more clearly now than was previously possible.

There are a number of important issues concerning the nitrogen cycle. What is the magnitude of the nitrogen fixation rate in major ecosystems? How much of this fixation is under the control of man, and how is the rate for fixation changing? Are anthropogenic disturbances to the nitrogen cycle causing a decline in the fertility and productivity of major terrestrial ecosystems? Are stores of nitrogen in major soil systems deteriorating? What effect does anthropogenic N have on rivers and coastal ecosystems? Is sewage N damaging (or enhancing) marine biotic resources? How has the concentration of  $\text{NO}_x$  and  $\text{N}_2\text{O}$  been enhanced by emissions from combustion and agricultural soils, and what effects may be expected on other important species, such as ozone?

### The Phosphorous Cycle

Figure 5 summarizes present views on contents of major phosphorous reservoirs and transfer rates between them. Phosphorous is abundant in the crust of the earth where it exists principally in the form of insoluble minerals (apatite,

iron phosphates) or as absorbed phosphate. These compounds are not available for biological uptake, and phosphorous is often a limiting nutrient in soils, in lakes, and perhaps in marine systems. Atmospheric transfer processes are unimportant for phosphorous, in contrast to carbon, nitrogen, and sulfur. Key exchanges are associated with dissolved and particulate transport in rivers, with weathering processes and with diagenesis in soils and sediments.

The total flux of phosphorous to the oceans can be estimated from present and preagricultural rates for continental denudation. The prehistoric rate was about  $10 \times 10^{12}$  gP  $\text{yr}^{-1}$ , while denudation rates at present are much higher, about  $35 \times 10^{12}$  gP  $\text{yr}^{-1}$ . Mining of phosphate for fertilizer accounts for an additional  $15 \times 10^{12}$  gP  $\text{yr}^{-1}$ , although not all of this is transferred immediately to rivers. The anthropogenic perturbation to the cycle of phosphorous is evidently large.

Much of the phosphorous in rivers is biologically unavailable, and a major question concerns the fraction of river-borne P which participates in the marine cycle, and the time scale for effective transfer to the ocean. Available P increases dramatically in the mixing zone between fresh river water and saline ocean waters. Some or all of this input may come

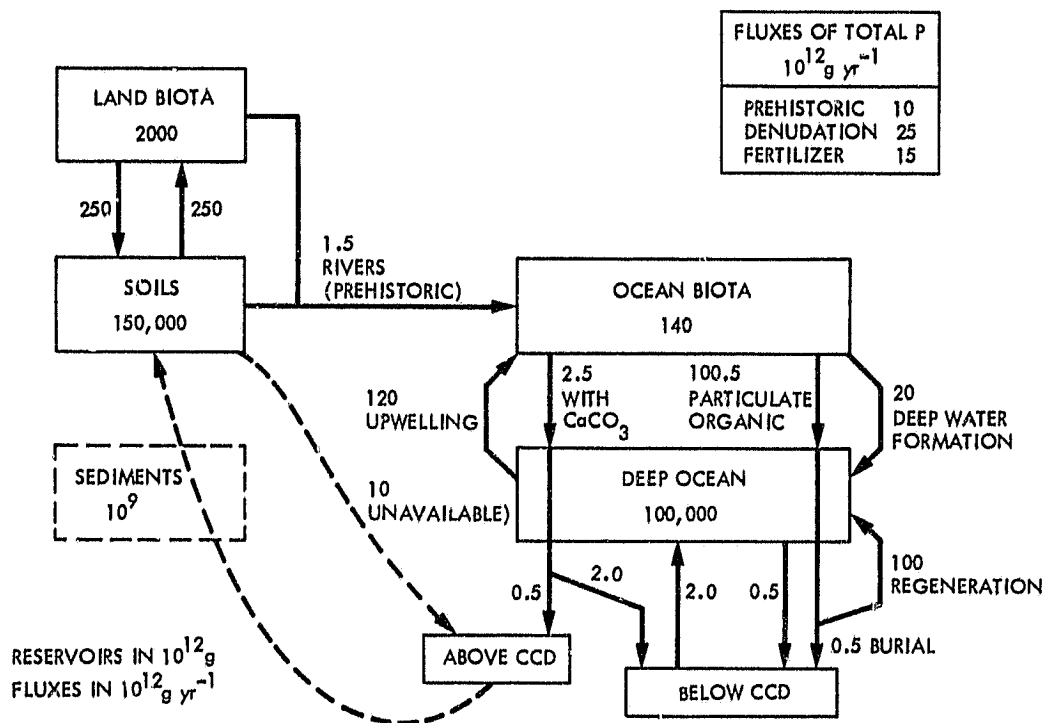
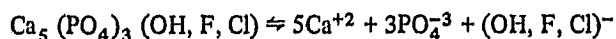


Fig. 5. Global cycle of chemically available phosphorous

from desorption or dissolution of particulate riverine P, enhancing the effective input to coastal ecosystems and to the ocean as a whole. The added P could arise also from marine sources, and much work remains to be done to resolve this question. Additional uncertainty is associated with storage of P in estuarine and coastal sediments. This phosphorous may be mobilized during periods of lowered sea level. Thus the land-ocean transfer rate shown in Figure 5 represents an average over geologic time, with large uncertainty concerning rates applicable at present.

Biological uptake of P in the photic zone of the ocean is extremely rapid, and surface waters are typically low in mineral phosphorous. Nitrogen and phosphorous are present in the ocean in almost exactly the ratio required by phytoplankton (16:1), and it is therefore difficult to discern whether marine productivity is limited by N or P. There is frequently a small residual of soluble P present in upwelled waters, after inorganic N has been exhausted, and hence the role of P is often assumed to be secondary. The absence of nitrogen fixation in this system is a puzzle. It has been argued that nitrogen fixation may be prevented by low levels of P, since N-fixing organisms appear to need high levels of P. Thus marine cycles of N and P may be tightly coupled in subtle ways, and it is difficult to unravel the human impact.

The factors regulating deep-ocean phosphorous are not well established. It has been pointed out that  $PO_4^{-3}$  is roughly in equilibrium with apatite and some have argued that the abundance of  $PO_4^{-3}$  might be controlled by the equilibrium



The chemical form of apatite in sediments is quite variable, however, and the time to establish equilibrium is long. It appears that  $PO_4^{-3}$  must be controlled kinetically by biological processes in the sea, but the basic mechanisms remain controversial. Similar remarks apply to the factors controlling the availability of P in terrestrial soils.

We need to address the following questions. What are the mechanisms controlling the availability of P in terrestrial soils, and how does the availability of P respond to anthropogenic perturbation (e.g., acid deposition)? What is the magnitude of the river-borne flux of P to the ocean? How is the chemical availability of this P controlled? Is productivity in the surface ocean limited by P? Would biological fixation of N increase dramatically in coastal areas in response to anthropogenic enhancement of river-borne P?

### The Sulfur Cycle

Sulfur compounds are present in all living material. Like nitrogen, sulfur exists in a variety of oxidation states, from -2 ( $H_2S$ ) to +6 ( $H_2SO_4$ ), and is cycled among those states by microbial and atmospheric reactions. Figure 6 summarizes present knowledge of the fluxes of sulfur compounds to and from the atmosphere. Reduced sulfur gases are emitted primarily as the result of biological processes in ocean surface water and in salt and fresh-water marshes, although volcanoes contribute a minor amount. These reduced gases are oxidized by tropospheric OH and by oxidants in droplets to  $SO_2$  and  $H_2SO_4$ . Industrial releases of sulfur, mostly as  $SO_2$  from the burning of fossil fuel, are comparable to current estimates of the natural source from biological processes, volcanoes, and sea spray.

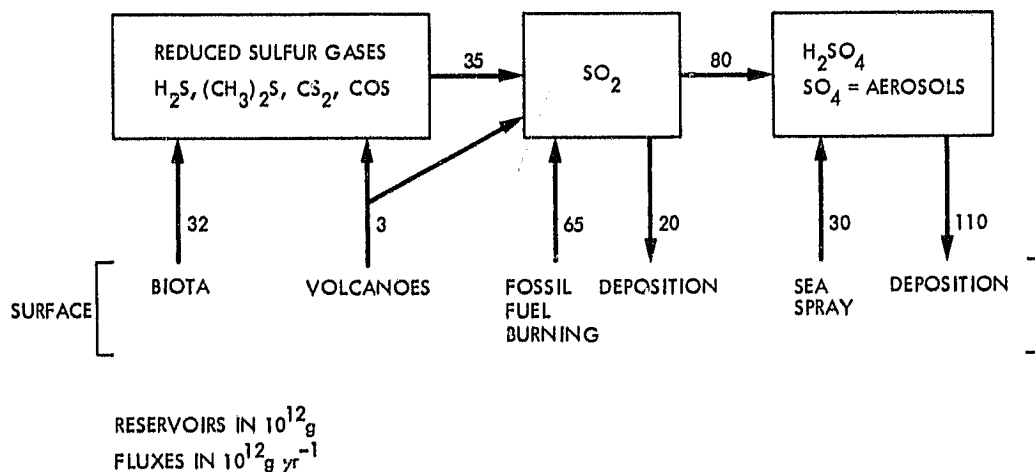


Fig. 6. Tropospheric sulfur budget

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Sulfur is in the -2 oxidation state in organic form, and is released mainly as  $H_2S$  during the decay of organic material. Sulfur-reducing bacteria gain energy by oxidizing organic carbon to  $CO_2$  using sulfate, which is converted in turn to  $H_2S$  or to sulfur compounds of intermediate oxidation states. These compounds may be oxidized by sulfur-oxidizing bacteria or they may be emitted to the atmosphere. Several measurements have been made of the fluxes of  $H_2S$ ,  $(CH_3)_2S$ ,  $CS_2$ , and COS in various locations (salt and fresh-water marshes in particular), but more needs to be done to define the biological sources of reduced sulfur gases in order to understand their dependence on environmental parameters, and to determine the extent to which they have been perturbed by anthropogenic activity.

Industrial releases of sulfur, primarily  $SO_2$  from fossil fuel burning, are concentrated in only a small fraction of the global land area. High concentrations of both  $SO_2$  and  $H_2SO_4$  are known to be harmful to plants, and concentrated emissions from industrial sources can lead to regional as well as local problems. The problems of acid rain in Eastern North American and Western Europe are well documented and must be regarded as phenomena approaching continental scales.

Longer-lived compounds, COS and  $CS_2$ , for example, may provide sources for  $SO_2$  and for sulfate aerosols even in loca-

tions remote from all known sources. These gases are associated primarily with biological processes, but release from industrial sources may also be significant. An anthropogenic contribution to COS and  $CS_2$  could be important since these gases may be important contributors to the stratospheric sulfate layer and could therefore influence the radiative budget of the earth.

The following questions should be addressed in connection with the sulfur cycle. What are the magnitudes of the biological fluxes of reduced sulfur gases? What processes control these fluxes and how have they been perturbed by human activity? What is the pattern of dispersion and chemical fate of industrially released  $SO_2$  and how does it affect the areas in which it is deposited as  $SO_2$  or acid rain? What controls the transformations of sulfur gases in the atmosphere? Are there substantial anthropogenic perturbations to the concentrations of long-lived gases such as COS and  $CS_2$  and thus to the stratospheric sulfate layer?

### The Water Cycle

Water required by the land-based global biomass is supplied by rainfall, from surface water, and from underground reservoirs. The latter two sources are extensively managed in many

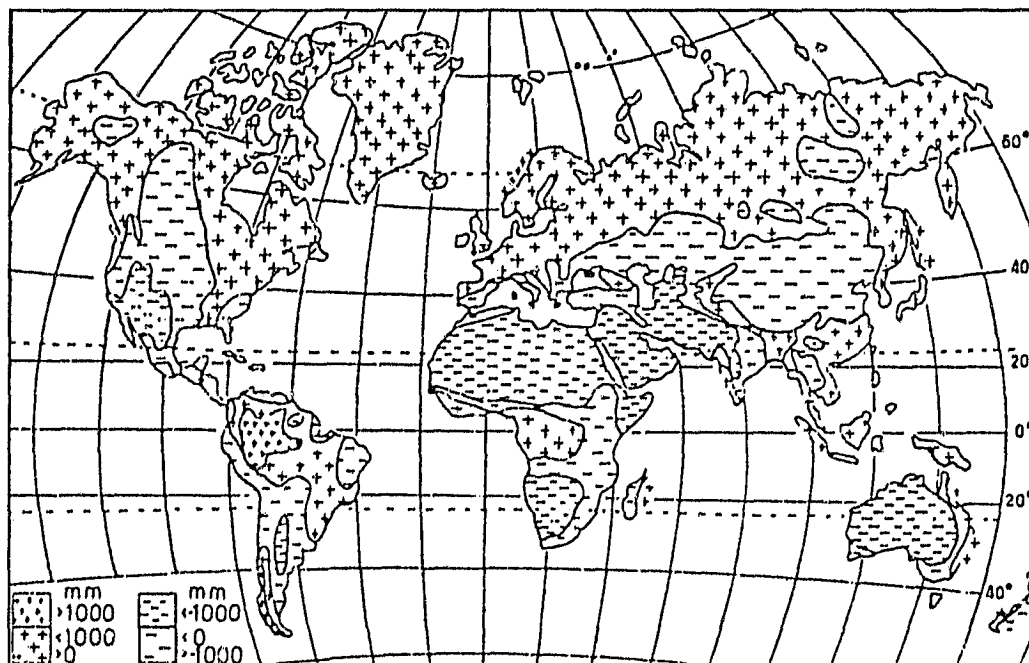


Fig. 7. Spatial distribution of water

countries for purposes of agriculture. Unfortunately, the spatial distribution of water (see Fig. 7) is highly variable over the globe and poorly correlated either with the density or rate of growth of the human population. Similar inequities arise in the temporal distribution of available water. Rainfall integrated over periods as short as a week or so is important to the productivity of unirrigated soils. Surface fresh water reservoirs are sensitive to rainfall integrated over time scales of 1-10 years and ground water responds to rainfall integrated over  $\sim 10^1$  to  $10^3$  year time scales. An ability to predict and thus better manage the delivery of water to food crops on the 1-100 year time scale would be invaluable to agriculture.

The importance of the hydrological cycle in connection with food production and human health has long been recognized. The U.S. Water Resources Council listed a number of critical hydrological problems needing urgent attention including: inadequate surface water supplies; overdraft of underground water; pollution of water supplies; flooding, erosion and sedimentation; and degradation of bay, estuary, and coastal water. These problems are common to most of the world's heavily populated areas and are particularly harmful in many developing countries. The scientific base for attacking many of these problems is not yet in place. Ten years ago, the U.S. National Science Board highlighted the need for better

knowledge of water supply and use, evapotranspiration, vegetative microclimates, and soil water storage. It is sobering to note that these needs still exist today.

Certain of the problems concerning the cycling and availability of water may be considered as local. Others transcend national boundaries and may be properly defined as global. The latter are associated, for example, with the variability of rainfall on regional and larger scales, with changes in gross vegetative type and cover on the land, and with the long-term availability of fresh water.

Our quantitative knowledge of the global water cycle is in fact surprisingly poor. One assessment is shown in Fig. 8. The volumes of water in ice and snow, underground water, and surface water are known to only  $\sim 50\%$ . Even more significant, evaporation minus precipitation over land and ocean (or equivalently the net flow of water from land to oceans in rivers and the net advection of moisture from the marine to terrestrial atmosphere) is not known to within a factor of 2. Any attempt to understand and predict the delivery of water to the land-based biosphere is clearly hampered by such ignorance. In the following chapters devoted to the atmosphere, biosphere, and ocean the pertinent parts of the water cycle will be addressed in more detail.

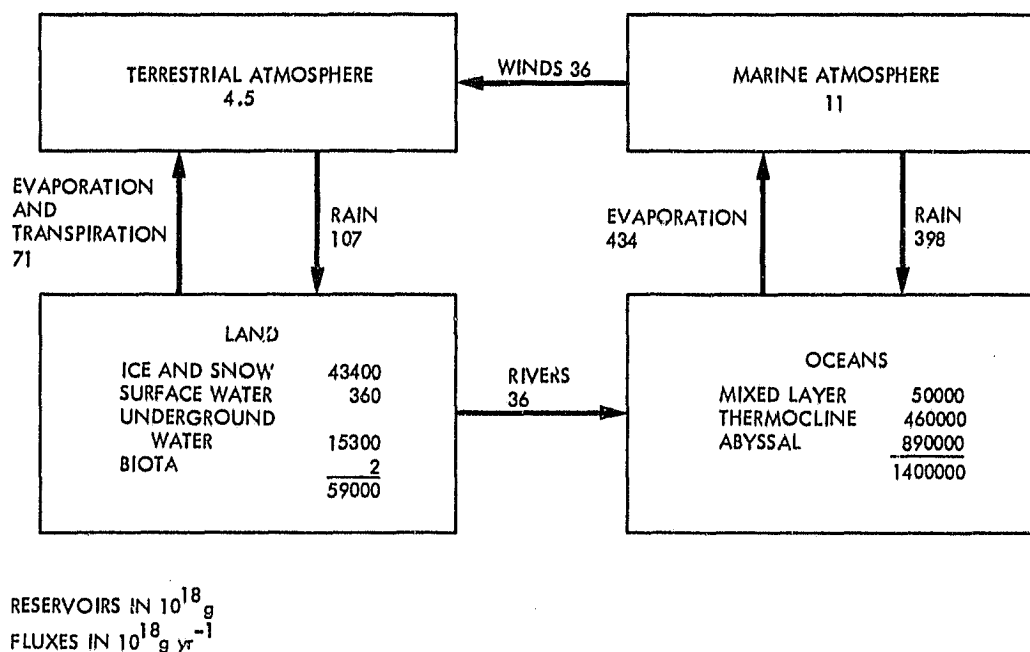


Fig. 8. Global water cycle

The emphasis here is on the water cycle as one of the most important of the biogeochemical cycles. The water cycle plays an equally important role in the circulation of the global atmosphere, atmospheric photochemistry, and in weather. Much of the heat which drives the atmospheric circulation involves phase changes of water; clouds, ice, and snow have additional important influences on the earth's radiation budget.

The fact that the global inventory of surface fresh water can be drained by evaporation and transpiration in 5 years or by rivers in 10 years points to the relevance of these measurements in the global biospheric water supply on the 5-100 year time scale addressed in this report. *We need a program of global measurements to improve our understanding of*

*evaporation, transpiration, atmospheric moisture advection, and river flow rates.*

Pertinent questions regarding the water cycle are as follows. What is the spatial distribution of available ground water over the globe and how is it changing in response to management by man? What are the spatial and temporal distributions of rainfall and evapotranspiration over the landmass and how do these distributions respond to changes in regional land use and to global climatic change? What is the budget of rainfall over land and ocean and how is it affected by oceanic circulation? What is the volume of ice and snow over the globe and how does it vary in space and time? What is the magnitude of the net flow of water to the oceans via rivers and how does this vary?

### III. Atmosphere

Primary areas of atmospheric research relevant to the issue of global habitability involve the hydrological cycle, the concentration of ozone in both the stratosphere and troposphere, and the chemistry of tropospheric species composed of carbon, nitrogen, sulfur and halogens.

The atmosphere plays a crucial role in the hydrologic cycle. It is the link which transfers fresh water from oceans to continents, redistributes water within continents, and influences the productivity of the biosphere. Water vapor is directly involved also in the atmospheric chemistry of C, N, S and halogen compounds. Water droplets and water vapor affect climate through the absorption of infrared radiation and through the scattering and reflection of incident sunlight by clouds. *The goal for the study of the atmospheric water cycle is to understand the factors which influence the spatial and temporal distribution of precipitation, clouds, and water vapor.*

Ozone plays an essential role in shielding the earth's surface from biologically detrimental radiation in the ultraviolet part of the solar spectrum (UV-B). Tropospheric ozone can adversely influence biospheric productivity by direct contact. Stratospheric ozone controls the temperature structure of the stratosphere, and thus its modification will affect directly the transport of trace gases within the stratosphere and may have consequences for weather and climate. *The goal for the study of atmospheric ozone is to understand quantitatively the chemical, dynamical, and radiative processes which control the spatial and temporal distribution of tropospheric and stratospheric ozone and to define its susceptibility to change associated with either natural or anthropogenic processes.*

The homogeneous and heterogeneous transformations of C, N, and S in the troposphere play a key role in biospheric productivity, in the fixation of atmospheric CO<sub>2</sub>, in deposition of N and S, and in the production and removal of tropospheric oxidants. Also important is the possibility of climate change due to increasing atmospheric concentrations of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, halocarbons, and tropospheric ozone. The urban environment is an important source for species such as CO, NO<sub>x</sub>, and heavy metals. The magnitude of its influence must be understood. *The major goals for the study of tropospheric chemistry are: (1) to define natural and anthropogenic processes which regulate the distribution and abundance of lower atmospheric oxidants, notably O<sub>3</sub>, SO<sub>2</sub>, and NO<sub>2</sub>, (2) to define factors which influence the chemistry of deposition, both dry and moist, (3) to identify processes which control the abundance of aerosols and of gases such as CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>, NH<sub>3</sub>, and halocarbons, and (4) to assess the impact of*

*infrared absorbers of anthropogenic origin on the radiative budget of the atmosphere and climate.*

The hydrologic cycle is a key to atmospheric chemistry through its control of water vapor, which by reaction with a photolytic product of ozone produces the primary source of the OH radical in the troposphere and stratosphere. In a more complex manner, the hydrologic cycle interacts with the biosphere through rainfall and evapotranspiration and also with the general energy budget and climate through the transport of latent heat and the formation of infrared absorbers and clouds.

The atmosphere's part in the water cycle has been studied for the last two decades with the help of numerical models of atmospheric dynamics. In their simplest forms these models predict precipitation of water directly from rising air. In more complex treatments attempts are made to parameterize the formation of clouds and to allow for their impact on both solar and terrestrial radiation. These General Circulation Models (GCMs) cannot be adequately tested because we lack sufficient data on the three-dimensional distribution of clouds and their radiative properties. The feedback relationship between clouds, the present climate state, and precipitation remains unclear. On the smaller scale we also require validated models for cloud formation and precipitation events. Processes occurring at the interface between land and atmosphere are poorly understood, but GCMs are presently modeling evaporation from the land, which depends on soil type, plant cover, topography, and mixing of the planetary boundary layer. Little is known of the importance of oceanic conditions for evaporation and, most importantly, there are few data either for precipitation or for evaporation over the ocean.

Stratospheric ozone has received widespread attention, both scientific and popular, over the past decade due to concerns about pollution of the stratosphere by various anthropogenic halocarbons (e.g., CFCl<sub>3</sub>, CF<sub>2</sub>Cl<sub>2</sub>, CCl<sub>4</sub>, CH<sub>3</sub>CCl<sub>3</sub>, etc.), by exhaust gases from supersonic aircraft (NO<sub>x</sub>), and increasing concentrations of N<sub>2</sub>O. These pollutants result in increasing concentrations of photochemically reactive ClO<sub>x</sub> (Cl, ClO) and NO<sub>x</sub> (NO and NO<sub>2</sub>) radicals which participate in reactions destroying ozone. Additional complications are associated with increasing concentrations of CO<sub>2</sub>, which change the temperature of the stratosphere, altering rates for several key reactions and possibly resulting in an increase in stratospheric ozone. As noted earlier, there are indications that the concentration of CH<sub>4</sub> has risen significantly over the recent past. Such a change would affect stratospheric ozone by modifying the partitioning of chlorine between HCl and ClO<sub>x</sub>, and also by altering the concentration of stratospheric H<sub>2</sub>O which is formed in part by oxidation of CH<sub>4</sub>. Consequently, it is necessary to understand how

stratospheric ozone responds to simultaneous changes in the stratospheric abundance of CFMs,  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{NO}_x$ . While more than 85% of atmospheric ozone resides in the stratosphere, the tropospheric contribution is also important in protecting the earth's ecological systems from ultraviolet radiation. We need to understand quantitatively the processes which control the distribution of tropospheric ozone as well as stratospheric ozone.

Recent reports by the National Academy of Sciences and by the World Meteorological Organization and by NASA discuss current understanding of the ozone layer and the influence of enhanced ultraviolet dosages on living organisms. While considerable progress has been made, outstanding problems remain. Accurate measurements for important radicals such as OH and  $\text{HO}_2$  are lacking. Few data, if any, exist for temporary reservoir species such as  $\text{H}_2\text{O}_2$ , HOCl,  $\text{ClONO}_2$ ,  $\text{N}_2\text{O}_5$ , and  $\text{HO}_2\text{NO}_2$ . We particularly need observations of the photochemically ubiquitous OH radical to define its altitude profile and its diurnal, latitudinal and seasonal variations. There are significant disagreements between theory and observation for source species such as  $\text{CFCl}_3$ ,  $\text{CF}_2\text{Cl}_2$ , and  $\text{N}_2\text{O}$ , for radical species such as ClO and  $\text{NO}_2$ , and for other important species such as  $\text{HNO}_3$ . These discrepancies call into question the validity of the models, both one-dimensional and two-dimensional, for prognostic purposes. Current models tend to emphasize either chemical, dynamical, or climatological processes. Completely interactive models linking all three processes in three dimensions are required. Water vapor is one of the primary species involved in stratospheric photochemistry, but the mechanism for transport of water vapor into the stratosphere is not well understood, and the effect of changes in atmospheric temperature on water vapor transport is still uncertain. Another important issue concerns the adequacy of recorded data which may be just now capable of defining trends over the past few decades for both the total column abundance and vertical distribution of ozone. It is essential to differentiate between trends and atmospheric variability and between natural and anthropogenic influences.

There are major unresolved questions concerning the temporal and spatial distribution of sources and sinks for gases such as  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{C}_2$  and  $\text{C}_3$  paraffins,  $\text{N}_2\text{O}$ , oxides of nitrogen, ozone, and others. In addition to the direct human input, we need to define the secondary effects of human activity on natural sources and sinks through deforestation and through changes in agricultural practice. Current instrumentation is barely adequate to determine the concentration of several source molecules. Accurate measurement of these species is essential for determining fluxes from natural ecosystems, a difficult but necessary challenge for the future.

Important chemical transformations in the atmosphere often involve oxidation of partially reduced gases formed by biological activity, such as  $\text{C}_x\text{H}_y$ ,  $\text{CH}_3\text{Cl}$ ,  $\text{CH}_3\text{Br}$ ,  $\text{H}_2\text{S}$ ,  $\text{CS}_2$ , and other reduced sulfur compounds. The complicated oxidation chain involves both OH and  $\text{O}_3$ . Changes in the NO and  $\text{O}_3$  concentrations on a global, or even regional scale, may set the pace for photochemical cycles, regulating the lifetimes for many of the C, N, and S gases important in stratospheric photochemistry. Ozone initiates radical chain reactions in the troposphere through the OH radical, formed by reaction of water vapor with  $\text{O}(^1\text{D})$ , a product of  $\text{O}_3$  photolysis. Both OH and  $\text{O}_3$  are sensitive to human intervention since their steady-state concentrations are affected by species for which there are known anthropogenic sources; CO,  $\text{CH}_4$ , and  $\text{NO}_x$  for example. Indeed, tropospheric ozone appears to be increasing not only in polluted air but also in clean regions of the troposphere. An important natural source for  $\text{O}_3$  involves transport from the stratosphere, but in situ photochemistry is also significant and may dominate the observed trend.

Deficiencies in our understanding of OH may be attributed to the lack of reliable global observations for key species controlling the distribution of OH (e.g.,  $\text{H}_2\text{O}$ ,  $\text{O}_2$ , CO, NO,  $\text{CH}_4$ ), and to the lack of accurate measurements for radicals such as OH,  $\text{HO}_2$  and NO. While our knowledge of homogeneous gas phase reactions is quite advanced, uncertainties are still associated with reaction mechanisms and with the dependence of rate coefficients on total pressure and water vapor concentration. Our understanding of homogeneous liquid phase reactions (e.g., within water droplets) and heterogeneous gas-liquid and gas-solid reactions is more rudimentary. Accurate models for these processes are essential if we are to define and describe the mechanisms operative in wet and dry deposition.

Studies of atmospheric water and precipitation, as required for the habitability program, are similar to those of the World Climate Program. Some elements are presently included in the NASA Climate Program. An important new component appropriate to NASA is measurement of global rainfall and measurements of evaporation and evapotranspiration over land and ocean. Present estimates for precipitation over the ocean are based on data with poor spatial and temporal sampling. Attempts are under way to infer precipitation from satellites, but these are limited to small-scale cloud systems. The principal immediate tasks are (1) to develop tools capable of measuring the amount, distribution, and variability of global rainfall, and (2) to develop an understanding for the processes at the air-sea interface as well as the air-biosphere interface.

The stratospheric program focuses on ozone and addresses the following significant processes: (1) transfer of material

and energy across the tropopause, (2) gas phase chemistry that controls the ozone layer, (3) formation and stability of an aerosol layer, and (4) transport of energy and chemical constituents within the stratosphere. The program aims to develop the scientific base needed for a fully interactive GCM. There is particular need for the measurement of fluxes of water vapor and other source gases between the troposphere and stratosphere. Where photochemical lifetimes are short compared to dynamical lifetimes, simultaneous measurements of photochemically coupled chemical constituents are needed along with temperature, pressure and the radiation field. We require also global climatologies describing vertical distributions of ozone and key hydrogen, nitrogen, and chlorine species, solar flux and atmospheric temperature. The Upper Atmosphere Research Satellite (UARS), proposed for launch in the late 1980s, is an important component of the program. The instrument complement for this mission has been selected to yield simultaneous measurements of chemical composition, temperature, winds, and incoming solar radiation. UARS should provide important contributions to our understanding of the coupling between the chemical, dynamical, and radiative processes of the stratosphere.

The tropospheric program has a strong focus on the interaction of the biosphere (including humans) with the atmosphere. Specifically, there is a requirement for data on the sources and sinks (both natural and anthropogenic) of the nutrient elements (C, N, and S) and toxic compounds (i.e.,  $\text{NO}_2$ ,  $\text{SO}_2$ , and  $\text{O}_3$ ) and on the concentration of intermediate species formed during chemical transformations in the atmosphere. Survey measurements over a global range of conditions are needed to define the distribution of trace gases such as  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{NH}_3$ ,  $\text{NO}_x$ , and  $\text{O}_3$ , whose lifetimes range from about a day ( $\text{NO}_x$ ) to several years ( $\text{CH}_4$ ). The role of the stratosphere in the supply of  $\text{O}_3$  and possibly  $\text{NO}_x$  to the troposphere needs to be studied, particularly near regions of strong troposphere-stratosphere exchange. Hemispheric differences in concentrations of trace gases, seasonal effects, and short-term variations all provide useful information. Broad geographic coverage is necessary to match the great diversity in types of sources and sinks over the globe. Long-term observations are required to identify trends. These characteristics—global and long term—require a satellite system utilizing both passive and remote sensors. The observational data to be gathered in this program would be analyzed with models ranging from one-dimensional studies with detailed photo-

chemistry to three-dimensional GCMs incorporating simplified chemical schemes. Mesoscale models represent an intermediate between these extremes and may prove useful in selecting aircraft sampling strategies.

A program of in situ measurements with a carefully designed sampling strategy is required. Evaluation of the global loss rate for soluble trace gases requires measurements of the chemical composition of rainfall and the extent and chemical composition of dry deposition from the atmosphere. Aerosols play a key role in atmospheric cycles involving nutrients, either through gas-to-particle conversion ( $\text{SO}_x$  and  $\text{NO}_x$  to sulfate and nitrates, for example) or through direct transport of particles through the atmosphere. Improved experimental techniques must be developed to sample aerosols in situ and to collect them for detailed analysis in laboratories. Improved models for aerosol formation are needed to relate measurements of chemical composition, size distribution, and optical properties to rates and mechanisms of aerosol formation.

The following points can be made in summary. There is a strong NASA program addressing key problems in the stratosphere relevant to global habitability. These include the distribution and abundance of stratospheric ozone and its sensitivity to anthropogenic influence, and the transport of gases and energy across the stratosphere-troposphere boundary. This program needs to be strengthened with the addition of a satellite program for global measurements, and an equivalent program needs to be developed for the troposphere. The chemistry part of the troposphere program should include studies of the spatial and temporal distribution of ozone and other atmospheric oxidants, studies of the processes which control the abundance of trace atmospheric gases and aerosols, and an examination of the chemistry of wet and dry deposition. New methods are required for measurement of the concentration and fluxes of key tropospheric species, and more global, long-term observations are required. Water is a principal player in the chemistry of the troposphere and both its chemistry and transport need to be well defined. The factors which influence the spatial and temporal distribution of water vapor, clouds and precipitation need to be understood. Insofar as climate change may affect chemistry through changes in temperature and transport, it is important to assess the impact of anthropogenic infrared absorbers on the radiative budget of the atmosphere.



#### IV. Land Biosphere

The terrestrial biosphere is in many respects the most important medium of interest for the global habitability program. It represents our greatest challenge. It is heterogeneous in time and spatial extent, ranging from regions of tropical forest, where temperatures seldom fall below 18° C, to desolate, perpetually snow- and ice-covered regions near the poles. It includes the tropical savannas, the steppes, the deserts, grasslands, deciduous and boreal forests, and arctic tundras. It encompasses extensive areas devoted to agriculture and other forms of modern anthropogenic activity. It is continually changing in response to shifting patterns of climate and to various forms of human activity. Fully 10% of the total land area of the planet has been transformed over the age of man to meet an increasing demand for food, fibre and timber. Changes have been brought about, for social and economic purposes, by extensive applications of modern technology, by the widespread use of chemical fertilizers and pesticides, by mining of ground water, by redirection of surface water reserves, and more recently by genetic manipulation of plants. Changes are in many instances global in consequence. The global habitability program will seek to provide the body of knowledge required to assess the significance of these changes, and to provide the information base required for purposeful future development of the resources of the planet.

Our overall goal is to develop an understanding of the terrestrial biosphere as an integrated system, to understand the significance of the internal dynamics which link individual components of the system, and to define the important interactions which couple the terrestrial system to the atmosphere and ocean. In keeping with the theme of this document, we focus primarily on the role of the biosphere in the cycling of water and on the cycling of the critical elements C, N, P and S in the biosphere. Our subsidiary goals are three fold: to define the present state of the terrestrial system; to monitor the system for significant alteration; and to develop the body of knowledge required to predict consequences of present and anticipated changes.

Historically, humans established their civilizations and food chains by modifying existing ecosystems. The net result of these activities usually involved ecological transformations driven by the continuous removal of biotic stocks. When aboriginal humans conducted these activities in the past, the magnitude of disturbance was small and homeostasis of ecosystems was unaffected. Today the earth's population is large and highly industrial, so that the need for biotic resources requires major exploitation of ecosystems, resulting in alteration of the underlying biogeochemical cycles.

When a terrestrial ecosystem is subjected to major disturbance, transformation of a forested area to crop land for example, organic matter and nutrients may be lost to stream-water and/or to the atmosphere. These losses are due to a variety of factors, including higher soil temperature and moisture content, faster decomposition, lower rates for primary production and plant nutrient uptake, and increased erosion. In land converted to agriculture, the water budget is altered and C, N, S, and P levels often continue to decline for many years. More than half of the carbon and nitrogen present in native prairie or forest may be lost during the development of agricultural land. When disturbance is followed by secondary succession (the reestablishment of vegetation and nutrient cycles), organic matter and nutrient levels accumulate on site. Material is added by photosynthesis, by precipitation, by fixation of nitrogen from the atmosphere, and by weathering of rocks. Secondary succession provides a transient decrease in standing stock and is followed by regeneration to former levels of biomass and nutrients, while changes following land clearing lead to progressive alterations, and, ultimately, to a new, lower equilibrium state. Consequently, total nutrient and biomass content of an ecosystem or vegetation class varies with the initial ecosystem type and with time since, and the nature of, the disturbance.

The rate of global land clearing is uncertain, and the global extent of agricultural systems is unknown. Estimates of cropland in North America vary by 50%. Recent estimates of clearing of tropical forests for agriculture vary greatly. Reports by the National Academy of Science and FAO-Agriculture differ by 500%. FAO data on rates of clearing of closed canopy tropical forest for agriculture differ by 100%.

The difficulties of biome-wide assessment reported in many studies are in part due to the nature of the method of data acquisition. For instance, FAO-Agriculture relies heavily on primary data from national governments. In many tropical countries, cutting and clearing data may be outdated or may represent no more than informal estimates. There has been, however, recent progress toward more accurate assessments of deforestation in tropical forests. FAO-Forestry surveyed 76 tropical countries, representing 93% of the tropical area. This study concluded that in 1980,  $7.5 \times 10^4$  km<sup>2</sup> of closed canopy forest were cleared for agriculture. The study projected an annual clearing rate from 1981 to 1985 of  $11.3 \times 10^4$  km<sup>2</sup> yr<sup>-1</sup> in closed and open tree formations with an annual logging rate of  $4.4 \times 10^4$  km<sup>2</sup> yr<sup>-1</sup> in undisturbed tropical forests.

The most promising approach to measuring changes in land use and biomass densities on a global scale involves satellite imagery. World-wide coverage, prohibitively expensive by other means, has been available since 1972. Satellite

imagery has been used to measure areas of various agricultural crops, disease in crops, area and rates of harvest of forests, and dimensions of cities.

The objectives for studies of the land biosphere are as follows:

- (1) To establish the areal extent of major terrestrial ecosystems with particular attention to definition of factors influencing the dynamics of ecosystem boundaries
- (2) To establish biomass densities for each of these systems, i.e., to determine the magnitude of standing crops of carbon
- (3) To obtain quantitative information on the C, N, P and S content of soils in these systems
- (4) To determine rates of net primary productivity and respiration
- (5) To define the quantities of N, P, and S available in individual biomes and to identify and quantify processes responsible for major sources, sinks, or transfers of these elements
- (6) To identify and focus studies on regions subject to particularly rapid change with the view to defining the underlying reasons for change, to forecasting the future evolution of such systems and to defining possible impacts on other biomes and on the atmosphere and ocean
- (7) To study the water budget of major systems to define factors influencing both input and removal of  $H_2O$  including the role of ground water reserves.

To address these objectives, the land area of the earth must be divided into a number of ecologically meaningful regions. Several approaches to this task have been suggested. Some groups have used grids of latitude and longitude, while others have defined a series of biomes (tropical forest, alpine tundra, natural grassland) and determined the areal extent of each biome in a range of geographical areas. An approach to land classification based on the Holdridge Life Zones seems the most promising. In this scheme, temperature and moisture are assumed to provide an adequate statistical estimator of biomass and soil carbon stocks in most of the biomes of the planet. It is further presumed that these parameters can be sampled globally with accuracy and efficiency. These assumptions must be tested. If the Holdridge classification scheme proves successful, the (potential) areal extent of different ecosystems can be established using climate data from the World Meteorological Organization and other such sources.

Remotely sensed climate data may be easier to develop than traditional information on potential land cover. Furthermore, a land classification scheme based on climate data may allow a direct attack on the question of the effect of climate on net primary production.

The Holdridge system is focused on the potential vegetation of an area, and must be supplemented by a land-use scheme. In developing a land-use map for the planet, two measurement objectives should be pursued: first, a current land-use scheme needs to be developed; second, a method must be evolved to measure the rate of change in land-use.

The former is more difficult and more costly for at least two reasons. First, the determination of the successional stage of human-altered ecosystems is a far more difficult problem than simply determining a rate of disturbance. For example, a forest harvest in the tropics is easier to detect than the state of the tropical forest ten years after harvest. Second, a complete land-use inventory requires geographically extensive coverage, whereas detection of change can be approached through specific sampling strategies. Fortunately, once established, a land-use inventory can be updated readily by determining rates of change in land-use.

The major difficulty in land-classification schemes is the identification of successional states. Succession is especially important in forests because of their large carbon and nutrient content. The ability to recognize successional communities will hinge on their spectral characteristics, the precision with which these characteristics can be recognized on the ground, and the knowledge of the patterns and areas of succession for major vegetations. There are presently three technologies which may provide information germane to the description of biomass dynamics. These technologies are 1) LANDSAT-Leaf Area Index (LAI), 2) Imaging Spectrometer (IS) and multispectral reflectance, and 3) the Synthetic/Sidelooking Aperture Radar (SAR/SLAR).

The method currently employed to assess biomass storage and potential productivity from remote sensing uses the leaf area index (LAI) of plant canopies, expressed as layers of leaf area per unit land area. It has been shown for agricultural systems that quantities of water and carbon dioxide exchanged by vegetation are linearly correlated with LAI, at least within an LAI range of 2 to 7. It remains to be shown, given LAI, forest type, and region, that it may be possible to predict total net primary production. Further, if total plant biomass is to be determined, the total height of the canopy must be measured. These questions should be explored initially in selected regions with known gradients in these variables; for example, single species tropical forests, boreal forests with

a range of LAI, climatically steep-gradient forests in the Pacific Northwest, deciduous forests in the eastern U.S., savannas with a north-south gradient in tree density, and agricultural areas with a definite gradient in LAI.

A potentially valuable addition to LAI and biomass data could be provided by detection of the biochemical characteristics of canopy leaves. This may be done by measuring the reflectance or emissivity at several wavelengths. An anomalous signature detected in one biome may be correlated with the presence of a new species, which might allow recognition of successional states or other emergent properties and provide an important aid in determining rates of decomposition and nutrient cycling. Reflectance peaks in the infrared can be used to indicate leaf water content and, coupled with measurements of canopy temperature, might offer indirect evidence concerning stomatal state. Stomatal state, coupled with remotely sensed chlorophyll concentrations, could provide a basis for calculating net primary production. In addition, subtle absorption features occur in the IR which are related to cellular arrangement within the leaf and to hydration state. Cellular arrangement within the leaf is genetically controlled and is thus of taxonomic significance. This raises the possibility that plant community composition could be determined on the genus and species levels (successional state) for some ecosystems.

The SAR technology allows high spatial resolution, resulting in well-calibrated images of land surfaces under almost any atmospheric conditions at any time of day or night. This would allow us to monitor vegetation at critical stages of the diurnal cycle and the growth cycle. Clouds often preclude this option for optical instruments, particularly in the tropics. In addition, it may be possible to detect important features below the optical canopy. Strong correlations have been observed between radar backscatter and plant water content for some types of vegetation (primarily crops). Differences in backscatter have been used to distinguish between forests composed of deciduous trees, short needle conifers and long needle conifers. Clearcutting is particularly evident in radar images of forested regions, and there are studies underway to determine if soil moisture can be remotely sensed from orbit using radar techniques. More work needs to be done to fully determine the capabilities of remote sensing techniques to measure changes in the state of land biomass.

The cycling of carbon, nitrogen, sulfur, phosphorous, and water within the land biomass can be affected greatly by anthropogenic disturbances. A series of test regions should be established where baseline measurements, both ground-based and remote, of carbon and nutrient stocks and fluxes could be developed. Laboratory studies of the basic biochemi-

cal processes should be conducted in these test regions. Priority should be given to projects which measure the biogeochemical and ecological consequences of anthropogenic disturbances in five areas: large-scale temperate agriculture, boreal and tropical forests, savannas, and wetlands. The global habitability program should give special emphasis to temperate zone agriculture, since the world depends on this system for much of its food. Temperate zone agriculture is tightly linked to climate—particularly rainfall. Large changes in the stocks of carbon, nitrogen, phosphorous, and sulfur occur when a system is subjected to continuous cultivation, and industrial agriculture requires large anthropogenic inputs of water, nitrogen, phosphorous, and sulfur. Fortunately, there is an extensive data base on carbon and nutrient stocks which may be used to place industrial temperate zone agriculture in its global context, and in particular to establish the relationship of agriculture to the natural biogeochemical and climate systems of the planet.

In contrast, densities and fluxes of carbon and major nutrients in tropical and boreal forests are described only poorly in available data. Rates of disturbance in tropical forests are large, and the response of these systems to repeated harvest is not well understood. Savannas are significant in that they exhibit marked natural fluctuations in productivity, up to 500% between seasons, and they are currently subjected to large anthropogenic changes. The ratio of woody to grass vegetation influences the biogeochemical cycles in savannas since this ratio determines total carbon and nutrient storage, the season and rates of wet primary production, and turnover rates of litter (<1 year for grass, several years for woody vegetation). The ratio of woody vegetation to grass (and hence C:N:S:P) in the savanna regions changes in response to bush encroachment, clearing for arable lands, use of fire to increase grazing lands, and depletion of woody vegetation for firewood. The final priority area suggested is wetlands. Wetlands are a major potential source of reduced tropospheric trace gases. It is believed that wetlands are being lost worldwide at a rapid rate due to conversion to agriculture.

In summary, the goal of a terrestrial biosphere program is to understand the interplay between net primary production, human disturbance, and the cycling of water, carbon, nitrogen, phosphorous, and sulfur. This effort will require remote sensing to define the current state of the terrestrial biosphere and to quantify rates of change at the global scale. Space measurements must be coordinated with in situ measurements to define biological processes in representative ecosystems. Large scale characteristics of changing land use should be related to the microbiological cycling of carbon and nutrients using a hierarchy of sampling schemes with judicious application of models, laboratory studies, and process studies. Mea-

measurements of carbon and nutrient densities before and after perturbations will provide a basis for first order measurement of the fluxes of C, N, S, and P. Local data must be carefully related to changes observable from space, in order to allow

extrapolations to the global scale. Progress in understanding the interaction between elemental cycles, as well as progress in understanding the dynamics of these cycles, will arise as the underlying biological processes are revealed and quantified.

## V. Oceans

The oceans play a central role in carbon and nutrient cycles. They contain more than 90% of the earth's non-sedimentary carbon and nutrients, and they remove at least half of the anthropogenic carbon added annually to the atmosphere. The oceans have enormous heat capacity and they moderate fluctuations and latitudinal gradients of temperature. *A goal for the global habitability program is to develop an understanding of the ocean as a physical, chemical, and biological system, in order to assess its role in climate and in the major cycles of carbon, nitrogen, and phosphorous.* The present magnitude or rates for primary productivity, nitrogen fixation, and burial of organic debris, and the factors controlling them, are of particular and immediate interest.

Specific objectives for the ocean program are:

- (1) To determine the concentration of chlorophyll-a over extensive regions of the world's oceans and to make use of these and other data to deduce rates of primary productivity, differentiating between coastal zones where productivity may be limited by light and areas of the open ocean where supply of nutrients N and P may be more important
- (2) To study selected systems in order to clarify the role of physical, chemical and biological factors in regulating rates of productivity and to improve our understanding of processes regulating rates at which C, N and P are delivered to sediments, with particular attention to coastal and shelf environments where deposition may be most significant
- (3) To determine rates and identify processes responsible for transfer of chemical elements, particularly N and P, across the thermocline
- (4) To study regions at high latitudes, where intermediate and bottom waters are formed, to obtain information on rates and processes regulating removal of C, N and P from surface waters
- (5) To conduct similar studies of upwelling systems, with particular attention to regions where fixed nitrogen may be lost from the ocean by denitrification
- (6) To conduct studies both in the laboratory and in the field, to improve our understanding of processes and environmental factors regulating fixation of N, and to make use of this information to derive rates for fixation of N on a global scale
- (7) To establish relative abundances of C, N and P in representative coastal sediments in order to determine the availability of these elements for marine biota

under conditions where sediments may be eroded and released into the open ocean.

The photosynthetic activity of marine plankton, or primary productivity, is the most significant biological path through which inorganic carbon in seawater is converted to living material. The rate of productivity in coastal waters can vary in response to seasonal fluctuations in climatic conditions, and is limited usually either by light or by the availability of major nutrients such as nitrogen and/or phosphorous. Rates of productivity in the open ocean typically show less seasonal variation, and most data indicate that the process is nutrient-limited. Indirect evidence supports the hypothesis that large ocean-wide changes in primary production are linked to major glacial cycles, and mechanisms have been postulated involving feedback loops between the CO<sub>2</sub> content of the atmosphere, cycles of burial and resuspension of sediments, primary production, and glaciation.

The coupling of physical processes in the atmosphere and the ocean, such as the air-sea interactions that drive upwelling events and mix the upper ocean, and those that govern the continuous upward transport of nutrients across a thermocline, influence both the rate of photosynthesis and the fate of the material produced. Although the physical and the biological aspects of these interactions are either known or can be predicted for certain defined conditions, we lack the precision necessary, in both temporal and spatial dimensions, to extend our knowledge of these interactions to the global scale. This limitation is a result of the historic dependence of oceanography upon shipboard observations, and the consequent difficulty in generating a synoptic view of dynamic systems. Recent success with proof-of-concept missions for satellite sensors of ocean properties has revolutionized, in both a conceptual and methodological sense, the study of ocean features and processes. We now have the capability to view simultaneously, on relevant temporal and spatial scales, both the physical and biological aspects of some very important systems in oceanography. In concert with data from moored arrays and shipboard experiments, a new understanding can be synthesized that is directly applicable to the issues of interdependence among the atmosphere, the oceans and the marine biosphere.

The magnitude of primary productivity in the sea is approximately similar to that on land. For a variety of reasons, however, there is uncertainty, perhaps by as much as a factor of two, in the best estimates for the global magnitude of this flux in the marine realm. Recent values are reported in the range  $30-45 \times 10^{15} \text{ gC yr}^{-1}$ , but some investigators have argued that even the higher of these numbers may be conservative. Current estimates of marine productivity reflect compilations of data from decades of shipboard observations and

these data vary considerably in quality. As a result of improved remote sensing capabilities in the last few years, it is, however, now evident that a strategy combining the use of satellite-sensed ocean color and temperature, in concert with additional shipboard observations, can be effective in reducing significantly the uncertainty in estimates of global marine primary production.

More than 80% of the total plankton production occurs in waters beyond the limits of the continental shelves. The relatively narrow coastal or neritic region, about 10% of the total ocean area, supports the remaining 20% of the production, and it is here that both coastal upwelling and the well-documented "spring-bloom" phenomena of temperate latitudes occur. Coastal waters are about 3-6 times more productive per unit area than those of the open ocean. A visual impression might lead one to expect that the difference would be even greater, but the open ocean has less seasonality in production and its euphotic zone is deeper. There are important qualitative differences, however, between the plankton, the means for delivery of nutrients and the fate of the organic matter produced in the two regions.

The inorganic carbon utilized in primary production is readily replaced by  $\text{CO}_2$  from the atmosphere. Phosphorous and nitrogen, the other major nutrients required to support open ocean production, must come either from nutrient-rich water below the thermocline or, in the case of nitrogen, from atmospheric sources. Current estimates for the upward flux are derived from nutrient or temperature profiles, and are approximate at best. The role of physical processes, such as billow turbulence or breaking internal waves, could be significant in some regions, but has not been adequately quantified. The atmospheric sources for nitrogen, both as atmospheric wash-out of nitrate and ammonia and as diatomic nitrogen fixed by blue-green algae, typically supply less than 1% of the required nitrogen. Though nearly trivial in this context, the process of nitrogen fixation is of great interest. Within the blue-green algae, or cyanobacteria, only one genus (*Trichodesmium*), represented by a few species, commonly occurs in oceanic waters. It has an extremely slow rate of growth compared to other phytoplankton, and evidence is lacking to indicate whether it may be more productive under certain conditions. There are suggestions that the organism may have a high requirement for phosphorous and that the concentration necessary for optimal growth conditions is not typically found in near-surface waters.

The supply of nutrients to coastal regions is dramatically different. Here upwelling and the spring bloom phenomenon are critically important. With upwelling, the surface water advected offshore by winds is replaced by the upward movement of nutrient-rich water from below the seasonal thermo-

cline. The temporal and spatial scale of these events vary considerably between upwelling regions. Under some conditions, in the Eastern Tropical Pacific for example, the settling rate of organic material is sufficiently high that the demand for oxygen in the underlying water may exceed its supply, resulting in a condition of anoxia, favoring loss of nitrogen to denitrification. These localized systems may play an important role in the overall budget of fixed oceanic N—they could provide a sink sufficient to deplete the ocean's reserve of fixed N on a time scale of  $10^4$  yr or less, according to some estimates—and they obviously merit special attention. In the Humbolt Current, discrete patches of upwelled water several km across may persist for a few weeks, while in the California Current they are smaller and the dispersal of nutrients is more rapid. This rate of dispersal can have considerable influence on the nature of the plankton community which develops in response to the nutrient enrichment. The limitations of shipboard observations are obvious, and much of the uncertainty regarding the magnitude of the upward flux of nutrients, subsequent productivity and the possible role of denitrification in upwelling regions can be reduced with greater access to remotely sensed ocean color and temperature data.

The spring bloom occurs in response to nutrients mixed to the surface as a result of both the winter flux of heat from the sea to the atmosphere and the role of winter storms in mixing the water column. With progression towards spring, the combined effects of increasing day length and solar elevation, and decreasing storm action, result in a reversal of the sign of the heat flux, and the water column begins to stratify. The annual cycle of herbivorous potential is at its nadir in winter, and low rates of loss allow accumulation of phytoplankton biomass in the spring "bloom." The herbivores, typically copepods, respond to the increasing temperature and food supply with increased rates of reproduction. In time the winter charge of nitrate, phosphate, and silicate is depleted, and nutrient limitation in concert with grazing pressure lead to a reduction in primary production. Several decades of field observations, laboratory experiments, and mathematical modelling related to this annual cycle led to the general notion that most of the primary production is consumed by herbivores. Recently, however, a new synthesis of evidence from several continental shelf regions suggests that the largest fraction of the diatom production settles to the bottom uneaten. This phenomenon could provide a significant sink for carbon and merits further study.

Only a small fraction of the primary production, typically 5-20%, sinks out of the euphotic zone in the open ocean. Continual reprocessing of organic matter throughout the water column results in a refractory residue of both particulate and dissolved organic carbon. The fine particulate detritus is nearly ten times more abundant than living carbon, and the dissolved

material accounts for about 95% of total marine organic carbon. Easily identified components, such as lipids, carbohydrates, and proteins, constitute only a small fraction of the dissolved organic carbon. The bulk of the residual material is 4000-6000 years old. At steady state, maintenance of this reservoir requires an annual input of  $10^{15}$  gC, about 2% of the marine primary production.

Carbon exported to the deep carries nitrogen and phosphorus that must be replaced by a comparable upward flux. The near surface detritus is depleted in phosphorus due to more rapid remineralization of this element, and there is a slight excess of phosphorus, or phosphate, in near-surface waters. The delicate balance between the detrital loss and nutrient replacement sustains a rather uniform biomass and production in the open ocean. The subtle interactions between the physical and biological processes which regulate this balance are difficult to study and at present poorly understood. There are insufficient data, for example, either from laboratory or field experiments to test the recent hypotheses regarding the effect of a global dust cloud on marine primary production. It has been suggested that the direct effect of altered climate on ocean circulation and mixing could profoundly affect marine production.

Generalizations regarding the constancy of plankton composition, referred to as the "Redfield ratio," have recently received considerable attention from plankton physiologists. The early data compiled to yield the generalized ratio of C:N:P of 106:16:1 (atomic) were based largely on samples of phytoplankton bloom populations taken from coastal waters, sampled for the most part with nets. Laboratory studies have confirmed that these ratios closely approximate the composition of phytoplankton growing at maximal rates under optimal nutrient conditions. In a nutrient limited state, however, the elemental composition of the cells departs from the generalized ratio considerably. This finding is of significance relative to hypotheses that relate glacial cycles to release of sediment bound nitrogen and phosphorus, with resulting perturbation of atmospheric  $\text{CO}_2$  and marine primary production.

It is important also to understand the path by which organic matter reaches the sediment, since these processes definitely influence the composition of the particle at the time of burial. This point has been illustrated with data for particulate material collected at various depths in coastal waters during upwelling and nonupwelling conditions and in open ocean waters. The C:P ratios were high, but within factors of 1.4 to 1.6 of the Redfield ratio for material sinking out of upwelled waters; they were higher, factors of 2.2 and 3.2, for nonupwelling coastal waters, and highest, factors of 3.5 to 7.8, at the open ocean station. These findings sup-

port the notion that P is remineralized more rapidly than C as organic particles sink through the water column. The high C:P ratios in the least productive waters, even for near-surface samples, probably reflect the high rates of remineralization in the euphotic zone. Other data for this region suggest that productivity is not phosphorus limited. With respect to the organic phosphorus content of benthic sediments, the data are too scarce for generalizations suitable for application in large scale models. Published values for C:P ratios in coastal and oceanic sediments range from 250-620. Global models for nutrient fluxes have typically assumed a sediment C:P ratio of 106.

The biological aspects of problems relating to global marine production are among the most interesting and compelling for the global habitability program. We can identify at present four principal areas for research: (1) open ocean plankton distributions and productivity; (2) physical, chemical and biological interactions in mesoscale eddies; (3) productivity and sedimentation in coastal areas; and (4) physiological responses of important organisms to change in environmental conditions. Each of these requires a different combination of laboratory, in situ, and remote-sensing investigations. We need to apply new strategies to address research issues in the context of global atmosphere-ocean interconnections, and particular effort will be needed to acquire new insight into the underlying mechanisms to define the interactions which control marine systems. Strategies will involve carefully coordinated applications of satellite and shipboard technology. The NAS and NASA have recently presented examples of this type of approach in discussing issues on satellite oceanography and marine resources programs. There is a clear consensus among the oceanographers that satellite applications have the potential to revolutionize oceanography.

Efforts to improve estimates of global productivity should take advantage of recent improvements in the application of remotely sensed ocean color information to determine the baseline plankton concentrations for large areas of the ocean. Measurements are needed for periods of a few to several years, depending upon the area. They should be coordinated with observations of physical processes, including sea surface temperature, wind stress and current patterns, and with shipboard experiments at selected stations. Changes in plankton abundance could be documented and quantitatively related to the physical processes that drive these systems in the context of such a program. Special attention should be focussed on upwelling areas and/or zones for bottom water formation, since these regions have major influence on important biogeochemical cycles.

Improved understanding of air-sea interactions and mixing regimes should be sought from investigations of the shifts in

plankton populations and productivity that occur in meso-scale eddies. Satellite imagery of both sea surface temperature and color are critical in the design, execution, and data interpretation for such studies. Remotely sensed data allow one to track a particular mass of water, to follow its behavior during intervals between shipboard observations, and to use ship time efficiently while at sea. The Gulf Stream Ring Program represents a successful application of this kind of coordinated approach.

Multiplatform studies are definitely needed in representative coastal regions to study the fate of particulate organic matter sinking out of the near-surface waters. An excellent example of this approach is provided by the NASA-MAREX report. The MAREX program is intended to answer some important questions related to carbon storage in the sea. It sets the stage for a highly coordinated study that is itself strong justification for the next generation of ocean color scanners.

Shipboard and laboratory studies of plankton physiology are necessary concomitants to all of the above activities. Questions that can best be addressed in controlled laboratory experiments will arise as new data from field observations become available. For example, *Trichodesmium* is a unique nitrogen-fixing blue-green algae of the open ocean. We need to know whether its physiological state responds to changes

in ocean properties which can be related to climate. This organism and others with the same capability may be extremely important in the global biogeochemical cycle of N. Questions regarding the relationship between nutrient availability, organism composition, and the composition of organic remains which reach the sediment are other examples of issues that must be resolved by laboratory studies in order to best interpret findings from the field.

In summary, we need coordinated physical, chemical and biological studies of high latitude oceans to improve our understanding of processes regulating removal of chemical compounds from surface waters, a topic of particular significance to an improved definition of the carbon cycle. We envisage similar studies of the open ocean, focusing on factors influencing biological productivity, with special attention to transport of nutrients across the thermocline. We identify requirements for a variety of investigations in coastal zones, emphasizing interconnections between the coastal environment and the open ocean, on the one hand, and the land, including estuaries and wetlands, on the other. Upwelling systems in the Eastern Tropical Pacific are especially important in that these environments are thought to provide significant sites for denitrification. Attention is directed to needs for improved definition of factors influencing fixation of nitrogen and production of volatile sulfur. Focused studies are required to improve our understanding of the role of coastal sediments in the global cycles of C, N and P.



## VI. Atmosphere-Biosphere Interface

The atmosphere may be considered in many respects a chemical extension of the biosphere. Microbially mediated reactions provide dominant sources for  $N_2O$ ,  $NH_3$ ,  $CH_4$ ,  $H_2S$  and  $(CH_3)_2S$ , and perhaps for  $NO$  and  $NO_2$ . The biosphere is the major source also for various hydrocarbons, and for volatile halocarbons such as  $CH_3Cl$ . The interactions are not simply unidirectional. Carbon dioxide is exchanged rapidly between the atmosphere and biosphere. The lifetime for atmospheric  $CO_2$  measured with respect to this exchange is less than 10 years. The abundance of atmospheric  $CO_2$  can affect rates for exchange of  $H_2O$ . It is known that stomata of plants can open or close in response to lower or higher levels of  $CO_2$  with consequent effect on the water economy of the plants. Chemical reactions involving  $NO_x$  and hydrocarbons in the troposphere can lead to production and removal of  $O_3$ . The level of tropospheric  $O_3$  can have an effect on the health and productivity of the biosphere and may be particularly important for agricultural systems. Changing concentrations of  $N_2O$ ,  $CH_3Cl$  and  $CH_4$  may impact the chemistry of the stratosphere, leading to a modification of stratospheric  $O_3$ . An altered level of stratospheric  $O_3$  will influence transmission of ultraviolet sunlight through the atmosphere with a potential effect on biospheric productivity, and perhaps on the diversity of species in particularly sensitive habitats. An alteration in the release rates of various sulfur- and nitrogen-bearing gases can affect the chemistry of precipitation, leading to higher productivity in some environments, with possible negative effects in others, associated for example with the release of toxic metals such as aluminum. Gases such as  $O_3$ ,  $CO_2$ ,  $CH_4$ ,  $N_2O$  and  $NH_3$  can affect the radiative budget of the atmosphere, influencing climate, with complex consequences for individual ecosystems and the overall metabolism of the biosphere. It is essential that the interactions of the biosphere and atmosphere be considered in tandem. A change in one system can markedly alter the function of the other.

*A central goal for global habitability will be to elucidate the nature of the physical, chemical and biological processes regulating release and uptake of important chemical compounds by the biosphere and to clarify the response of the biosphere to an alteration in either the physical or chemical state of the atmosphere.* Early emphasis should be directed to the study of gases such as  $CO_2$ ,  $CH_4$ ,  $N_2O$ ,  $NO_x$  and  $SO_x$ , whose concentrations are known to be changing significantly at the present time.

Our understanding of processes affecting production and removal of  $N_2O$  has developed considerably over the past decade. Progress has occurred in an orderly way and could provide a model for the study of other gases. Observations

of specific systems, complemented by studies in the laboratory, offer clues to the nature of the mechanisms influencing  $N_2O$ . It is possible thus to relate studies of  $N_2O$  to studies of the overall global cycles of carbon and nitrogen. Nitrous oxide is produced in part by oxidation of  $NH_4^+$ , nitrification, and in part by reduction of  $NO_3^-$ , denitrification. An observation of  $N_2O$  in specific systems, in combination with measurements of  $NH_4^+$ ,  $NO_2^-$ ,  $NO_3^-$  and  $O_2$ , can be used to infer rates for important microbially mediated reactions, allowing a direct connection to the study of the biota. More remains to be done however. The concentration of atmospheric  $N_2O$  has risen by about 0.5 ppb per year (0.2% per year) over the past 20 years. An increase of this magnitude requires a source of approximately  $2 \times 10^{12}$  gN  $yr^{-1}$  as  $N_2O$ . A number of plausible explanations have been advanced to account for this rise but the issue remains unresolved. The nature and spatial distribution of the natural source is unknown. Most of the available data refer to aquatic systems or to terrestrial systems at temperate latitudes and there is an urgent need to extend scrutiny to selected tropical environments.

The situation for  $CH_4$  is less satisfactory. There is general agreement that the concentration of atmospheric  $CH_4$  has risen over the past decade and there is some evidence for a rise dating back to the 16th century. The magnitude of the recent rise is uncertain. Estimates for the trend in the last decade range from 1 to 2% per year. The lifetime for  $CH_4$  in the atmosphere is known to no better than a factor of 2 and the magnitude of the global source is similarly ill-defined. Methane is thought to be removed from the atmosphere mainly by reaction with  $OH$  in the troposphere. An improved definition of tropospheric chemistry would provide valuable information on the magnitude and perhaps the distribution of the source for  $CH_4$ . Studies of tropospheric chemistry must be supplemented by studies of selected ecosystems designed to elucidate the nature of the microbial processes responsible for production of  $CH_4$ . The rise in  $CH_4$  could reflect a lower concentration of tropospheric  $OH$  resulting in a longer lifetime, or increased production from either a larger population of ruminates or as a consequence of agricultural practices favoring crops, such as rice, grown in soils which are waterlogged for significant portions of the year. The explanation for the rise could be more subtle. It could relate ultimately to changes in land use, to the decomposition of lignin in forest areas cleared for agriculture. Careful investigation of selected systems, complemented by laboratory and atmospheric investigations, could provide the clues prerequisite to an understanding of the factors regulating release and consumption of  $CH_4$ . The task will not be easy, since microbial reactions are known to provide both sources and sinks for  $CH_4$ . Studies of the isotopic composition of  $CH_4$  in the atmosphere and in individual systems, in combination with biochemical investigations to clarify the nature

of the important processes, may be expected to play an important role in this endeavor. Similar remarks apply to strategies designed to improve our understanding of factors influencing production and removal of other hydrocarbons,  $\text{CH}_3\text{Cl}$ ,  $\text{NH}_3$ ,  $\text{NO}_x$  and sulfur compounds.

Carbon monoxide plays an important role in the chemistry of tropospheric OH and as such has a significant effect on production and removal of  $\text{O}_3$ . The northern hemisphere contains approximately 3 times more CO than the southern hemisphere. A portion of the excess CO is derived from combustion of fossil and biospheric carbon. Additional production is associated with atmospheric oxidation of  $\text{CH}_4$  and various hydrocarbons. We need to define the nature of these hydrocarbons and the factors which influence their production and decomposition. Atmospheric investigations may be particularly useful in this context. Lifetimes of many of the relevant hydrocarbons are controlled by reaction with OH and are quite short. It should be possible to identify significant source regions using atmospheric measurements as a diagnostic. Measurements of trace hydrocarbons might be additionally useful as indicators of biospheric productivity.

The importance of measurements of atmospheric  $\text{CO}_2$  in connection with general studies of the biosphere has been noted earlier. The biosphere may respond to changes in  $\text{CO}_2$  and this possibility requires further attention. Higher levels of  $\text{CO}_2$  may serve as a fertilizer, enhancing productivity. Higher levels of  $\text{CO}_2$  may also lead to more efficient use of

$\text{H}_2\text{O}$  by plants. Studies should be encouraged to refine our understanding of these processes. Such studies must be carried out on an ecosystem level and results should be incorporated in improved models for biosphere-atmosphere interaction. There is similar need to refine our understanding of the response of the biosphere to different ambient levels of  $\text{O}_3$ , to ultraviolet radiation, to temperature, to changing patterns of precipitation, and to variations in aerosol and precipitation chemistry. There are reasons to believe that all of these influences may be changing, and deficiencies in present knowledge preclude comprehensive assessment of their impact.

In summary, the objective to improve our understanding of the interaction between the atmosphere and biosphere requires quantitative data on the flux of key gases emanating from the biosphere. Progress will require careful studies of selected ecosystems, complemented by laboratory investigations designed to elucidate factors regulating major biogeochemical pathways. Ecosystem studies will involve both in situ and remote sensing observations. Measurements of  $\text{CO}_2$ ,  $\text{CH}_4$ , selected hydrocarbons, CO,  $\text{N}_2\text{O}$ ,  $\text{NO}_x$ ,  $\text{NH}_3$ ,  $\text{O}_3$  and various sulfur and halogen compounds at selected sites can provide a basis for the diagnosis of possible change in the chemical state of the atmosphere and biosphere. The measurement program should provide data for the principal chemical species in precipitation, recognizing the importance of the atmosphere as a path for large-scale redistribution of biospheric nutrients.

## VII. Atmosphere—Ocean Interface

The ocean exerts a major influence on several of the atmosphere's important trace components. It provides a sink for anthropogenic  $\text{CO}_2$  and oxides of nitrogen, a source (in coastal wetlands and productive areas) of  $\text{CH}_4$ ,  $\text{H}_2\text{S}$ , and  $(\text{CH}_3)_2\text{S}$ , a source of atmospheric halogens and  $\text{N}_2\text{O}$ , and a source of water vapor to the atmosphere. The magnitude of those sources and sinks, however, are not well known at present. *Studies of atmosphere-ocean interaction should emphasize measurement of gas fluxes and elucidation of the chemical, physical, and biological mechanisms controlling these fluxes.*

The ocean contains sixty times as much carbon as the atmosphere, and exerts a major control on the amount of  $\text{CO}_2$  in the atmosphere. However, in the natural cycle, the time scale for this control is about a thousand years, and shorter term transients can be significantly out of equilibrium with the ocean. The fate of anthropogenic  $\text{CO}_2$  has been the subject of considerable study over the past two decades. However, as noted in Chapter 2, there remains significant uncertainty about the amount of  $\text{CO}_2$  taken up by the ocean. Exchange of  $\text{CO}_2$  between the atmosphere and ocean is influenced by physical, chemical, and biological factors, which are quite non-uniform between various regions of the world's oceans. Therefore, models for  $\text{CO}_2$  exchange inevitably simplify the real ocean. Progress in this area must come both from additional and improved measurements, and also from more detailed and accurate elucidation of important processes.

The physical circulation of the ocean influences uptake of  $\text{CO}_2$  by determining the quantity of water in contact with the atmosphere annually. The "mixed layer" of the ocean (~75 m deep) exchanges with the atmosphere on time scales of between one month and a few years. The rest of the ocean is much more isolated from the atmosphere. The upper and deep layers exchange water by upwelling throughout the ocean, balanced by downwelling, or bottom water formation, at two locations in the polar seas. Subsidence of water in the great ocean gyres may also be significant. The rates of upwelling and downwelling are known only roughly (on the order of  $50 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ ). They give a lifetime for deep ocean water of about 1000 years. The depth of the mixed layer and its exchange with the deep ocean are critical parameters to models of oceanic uptake of  $\text{CO}_2$ , but the physical circulation of the ocean is not yet understood well enough to give accurate values to be used in such models.

The chemical interactions between gaseous and dissolved  $\text{CO}_2$  are described by fundamental chemical principles, and hence are generally understood. In sea water, inorganic carbon exists primarily in three forms: dissolved  $\text{CO}_2$ , bicarbonate ion ( $\text{HCO}_3^-$ ), and carbonate ion ( $\text{CO}_3^{2-}$ ). At a given amount of

total inorganic carbon ( $\text{TCO}_2$ ), the distribution of the species depends on the pH of the water, which is itself influenced by  $\text{TCO}_2$  and by titration alkalinity ( $TA$ ), which is approximately equal to the total negative charge contributed by carbon species.

Models of oceanic uptake incorporate these chemical principles, often in the simplified form represented by the Revelle factor  $R$ , which gives the change in  $\text{TCO}_2$  for a given change in  $P_{\text{CO}_2}$ :

$$R = \frac{\Delta P_{\text{CO}_2} / P_{\text{CO}_2}}{\Delta \text{TCO}_2 / \text{TCO}_2}$$

The challenge is to decide on the appropriate average or representative values of  $TA$ ,  $\text{TCO}_2$ , and  $R$  for the surface ocean, and the degree of equilibration between atmosphere and ocean.

Biological activity influences  $P_{\text{CO}_2}$  because fixation of  $\text{CO}_2$  into organic material changes  $\text{TCO}_2$ , and precipitation of  $\text{CaCO}_3$  (calcium carbonate) shells changes both  $TA$  and  $\text{TCO}_2$ . In particular, the degree of biological productivity in the polar regions where bottom water is forming may have an important influence on the ocean's uptake of fossil fuel  $\text{CO}_2$ .

Better understanding of the ocean as it affects  $\text{CO}_2$  requires additional information on  $P_{\text{CO}_2}$ ,  $\text{TCO}_2$ ,  $TA$  and nutrients in important regions (e.g., in the areas of polar seas where downwelling occurs). Detailed studies of other tracers for the ocean's physical circulation, and data such as might be provided by TOPEX, can also be very helpful to parameterizing the depth of the mixed layer and the rate of downwelling. Tracer studies include  $^{14}\text{C}$  and tritium from atmospheric testing of atom bombs, and chlorofluorocarbons, which have a recent and wholly anthropogenic source. Determination of the biogenic flux of C requires innovative strategies and careful modelling, using for example data on the isotopic composition of both dissolved and particulate carbon species.

The ocean is probably a minor source of  $\text{N}_2\text{O}$  to the atmosphere, but some uncertainties remain. There are two approaches to determining the flux of  $\text{N}_2\text{O}$  from the ocean to the atmosphere. The first is to make extensive measurements of the partial pressure of  $\text{N}_2\text{O}$  in the surface ocean and to use these data to estimate the global exchange rate. The major uncertainty in this estimate is associated with use of an average 'piston velocity' to relate supersaturation to  $\text{N}_2\text{O}$  efflux. The derived value for the global flux ( $\sim 1 \times 10^{12} \text{ gN yr}^{-1}$ ) must be considered uncertain to a factor of two or more.

Another approach is to study the production and consumption of  $N_2O$  associated with various processes in the carbon and nitrogen cycles. The results of such studies show that marine  $N_2O$  is produced largely during primary nitrification (microbial oxidation of  $NH_4^+$  to  $NO_2^-$ ). The yield of  $N_2O$  during nitrification is fairly uniform, about 0.3% N in  $N_2O$  for each  $NH_4^+$  oxidized. One can then estimate the global rate of nitrification from the ratio of nitrification to primary productivity. This reasoning gives a source of  $1.5 \times 10^{12}$  gN  $yr^{-1}$  of  $N_2O$ , using a primary productivity of  $30 \times 10^{15}$  gC  $yr^{-1}$  and 10% efficiency for oxidation of  $NH_4^+$  in surface waters. However, total primary productivity may be significantly higher than this, as discussed in Chapter V, and the efficiency for nitrification might also be higher. Hence, the total source of  $N_2O$  from the oceans could be greater than  $1.5 \times 10^{12}$  gN  $yr^{-1}$ . This question should be addressed by investigation of primary productivity and nutrient utilization, and by further studies of the production and consumption of  $N_2O$  during the cycling of carbon and nitrogen.

The evidence that the ocean is the main source of atmospheric halogens is largely circumstantial. The present atmospheric concentration of  $CH_3Cl$  is about 0.6 ppb. The mean lifetime of the gas is estimated to be 1.5 years, with reaction in the troposphere with OH the major sink. Thus, to maintain  $CH_3Cl$  at steady state, there must be a source equal to  $3.7 \times 10^{12}$  g.  $yr^{-1}$ . Present anthropogenic contribution of  $CH_3Cl$  is estimated to be  $0.3 \times 10^{12}$  g.  $yr^{-1}$  leaving a missing source of  $3.4 \times 10^{12}$  g.  $yr^{-1}$ . In open oceans  $CH_3Cl$  concentrations are extremely low ( $\sim 10^{-9}$  g.  $l^{-1}$ ) and nearly in equilibrium with the atmosphere. Hence no large sources are likely. Several investigators have observed higher levels near kelp beds distributed at various sites of the northern hemisphere, and elevated levels have been observed in the sea-atmosphere boundary layer in the tropical zone ( $20^\circ N$ - $20^\circ S$ ). Such observations imply that  $CH_3Cl$  may be biogenic in origin

with a tropical oceanic source. Preliminary data showing no north-south gradient has tended to reinforce oceanic sites as suspected sources, but important terrestrial sources cannot be ruled out. A better understanding of the role of the ocean as a source is essential to quantifying the global halogen cycle and assessing the impact of anthropogenic sources.

The ocean is an important component of the global sulfur cycle, but the magnitudes of sources and sinks are uncertain. The marine atmosphere contains detectable quantities of  $SO_2$ , COS, and sulfate aerosols, even in remote locations. Since the lifetimes of  $SO_2$  and sulfate are only a few days, there must be a local source in these regions, most likely reduced sulfur gases ( $H_2S$ ,  $(CH_3)_2S$ ,  $CS_2$ , and COS) released from the ocean and oxidized rapidly by reaction in the troposphere with OH or by other processes. These emissions would provide the natural background level for  $H_2SO_4$ , which in turn contributes to the acidity of local precipitation. The anthropogenic perturbation of the sulfur cycle is of the same order as, and locally greater than, the natural cycle, but confined to northern latitudes. In order to define the influence of industrial sources on remote regions of the atmosphere, the magnitudes and mechanisms for ocean-atmosphere exchange of reduced sulfur species must be better defined.

In summary, the flux of several important gases between the ocean and the atmosphere must be better quantified before we can understand the effects of anthropogenic perturbations to the natural cycles of  $CO_2$ ,  $N_2O$ ,  $CH_3Cl$ , and  $SO_2$ . Progress will come from more extensive measurements of the abundance of species in the atmosphere and ocean, from better values of the exchange coefficient and the effect of wind-induced mixing, from improved knowledge of the physical circulation of the ocean, and from better understanding of the physical and chemical mechanisms for emission and consumption of gases by the ocean.

## VIII. Land-Ocean Interface

Rivers, estuaries and coastal zones provide the major coupling between land and ocean. *A primary goal for global habitability will be to determine the fluxes of water, carbon, nitrogen, phosphorous, and sediment from land to ocean, and to elucidate the factors controlling these fluxes.* Rivers integrate the outputs from terrestrial ecosystems and provide sensitive indicators for changes occurring in these systems. *A secondary goal will be to study concentrations of dissolved and suspended material in rivers in order to measure changes in the state of major terrestrial ecosystems.*

The earth's coastal regions are important areas of biological and geochemical activity. The contribution of coastal waters to global biological productivity has already been addressed in Chapter 5. Coastal marshes may be important contributors to the global budgets of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and reduced sulfur gases (e.g.,  $(\text{CH}_3)_2\text{S}$ ). Of the interactions between the land and ocean relevant to the global habitability concept, the outflow of water from rivers is perhaps the most significant and most susceptible to perturbation on the 5-100 year time scale.

Outflow of fresh water from the world's rivers occurs at a sufficient rate to drain all lakes in only  $\approx 10$  years and to replenish the mixed layer in the world's oceans in  $\approx 10^3$  years. As noted earlier, present estimates of outflow from rivers may have errors approaching a factor of 2. Since the supply of fresh water to the continental biosphere is governed by the difference between inflow (net advection from the marine atmosphere) and outflow (from rivers), these outflow estimates need to be considerably improved.

Transport of carbon, nitrogen and phosphorous from land to sea represents one of the major links in the global cycles. As yet very little reliable information exists on the quantity of these elements transported annually by major rivers. The values so far reported in the literature range over an order of magnitude. Many reasons can be listed for this lack of precision. North American and European rivers have received higher research priorities than Asian, African and South American rivers, even though the latter are far more important in terms of discharge volume (see Table 1). Very few rivers have been studied systematically for several full hydrological years, and quantitative analytical techniques for various compounds and particulates in fresh waters have only recently been developed. Nitrogen and phosphorous behave nonconservatively in estuaries, but most often in opposite ways: nitrogen is removed in the saline mixing zone, while soluble phosphorous is added. It is unclear whether the nitrogen is denitrified, lost to sediments, or transported in particulate form. The source of phosphorous could be desorption from or

Table 1. The 20 largest rivers by continent and by water discharge

Continent	River		Water Discharge ( $10^3 \text{ m}^3 \text{ sec}^{-1}$ ), River	Total, Continent
	Rank	Name		
South America	1	Amazon	175	390
	3	Orinoco	23	
	10	Parana	15	
	19	Magdalena	7.5	
Africa	2	Congo	40	145
Asia	4	Yantze	22	450
	5	Brahmaputra	20	
	7	Yenisei	17.5	
	8	Lena	15.5	
	9	Mekong	15	
	12	Ganges	14.2	
	13	Irawaddy	13.6	
	14	Ob	12.5	
15	Amur	15		
18	Hsi	7.9		
North America	6	Mississippi	18	260
	11	St. Lawrence	14.2	
	17	Columbia	8.0	
	20	Mackenzie	7.4	
Europe	16	Volga	8	100
Total				1,400

dissolution of mineral phases, or mineralization of marine detritus. Thus, the amount of N and P supplied to the ocean is not defined. In short, existing data on riverine carbon and nutrients should be viewed with caution, especially for dissolved and particulate organic carbon and particulate nitrogen and phosphorous.

River-borne particulate material could play an important role in the carbon cycle, carrying perhaps a portion of the carbon lost from disturbed terrestrial ecosystems (the "missing carbon" discussed in Chapter 2). Degens argues persuasively that erosion of soils would account for the missing carbon, which may be deposited in coastal sediments without entering the atmosphere. For example, large increases have been reported in sedimentation in the Black Sea associated with disturbance of adjacent land areas. It may be further argued that organic losses from agricultural soils are stimulated by intensive fertilization. It is difficult to judge the validity of

these ideas, and of similar notions, due to the rudimentary state of knowledge about major river systems and coastal sediments.

Rivers play a major role in nourishing and/or polluting coastal ecosystems. The direct fertilization effect, due to river-borne nutrients, feeds regionally significant fisheries (e.g., Yantze River). Major floods may induce stratification of shelf waters in large areas, and where pollution loads are great, such as New York Bight or the Gulf of Mexico, anoxia may develop with devastating effects for the biota. The input of freshwater may be indirectly responsible for widespread coastal upwelling, due to density gradients. Coastal upwelling accounts for 10% of the marine carbon fixation, and this aspect of the marine carbon and nutrient cycles is most susceptible to large-scale perturbations over the next 100 years.

Rivers integrate the output of dissolved and suspended material from the continents. They provide the most direct means for determination of continental-scale changes affecting major terrestrial ecosystems. Perturbed ecosystems tend to evolve towards less efficient cycles for nutrients, minerals and carbon. Increased fluxes of these substances may be detected in rivers in response to anthropogenic perturbations or climate change. Discharge volumes for typical floods and low-flood periods respond strongly to development of lands in the watersheds of major rivers. Thus the hydrograph of a given stream, and its change over several years, gives direct information on perturbations to the hydrological cycle resulting, for example, from deforestation or destruction of wetlands. The alteration of flow patterns may have significant, large-scale effects in coastal regions of the ocean and on ecosystems and societies sited on the banks of major streams.

A program for the study of rivers requires in situ studies closely coordinated with remote sensing measurements of physical (i.e., flow), chemical and biological parameters. The great variability of rivers provides strong impetus for a combination of detailed in situ studies and long-term monitoring by automated observing instruments, possibly tied to satellite communications systems. Study areas should include the world's major rivers and their most important tributaries, their estuaries, and adjacent coastal waters. Four primary areas of study in the context of global habitability are: (1) fluxes of water to the ocean; (2) fluxes of carbon, nutrients, minerals, and sediment; (3) influence of rivers on major coastal/estuarine ecosystems; and (4) methods for monitoring rivers to detect large-scale changes in terrestrial ecosystems. The program must include mechanistic studies to elucidate controlling processes, as well as measurements of rates and fluxes. Objectives of the program are: (1) to determine accurately

water fluxes from land to ocean and to understand the geomorphological and biotic influences on total water volume and on variations with season, floods, and droughts, (2) to determine the magnitude of river-ocean transfer for carbon, nutrients, minerals and sediments, to understand the processes which control these fluxes, and to elucidate the response to human perturbations, (3) to determine the pathway of river-borne substances through coastal ecosystems, and the role of rivers in maintenance of the biotic resources of the sea, and (4) to define methods for using rivers as a major tool in monitoring terrestrial ecosystems and for quantifying changes due to anthropogenic activity or due to long-term changes in climate.

Programs of shipboard in situ observations should stress elucidation of mechanisms for chemical and biological transformations of nitrogen, phosphorous and carbon. Detailed studies are required in both polluted and unpolluted systems, in order to examine questions relating to anthropogenic perturbations. Observations from space must be obtained over long periods of time, since these are essential for an integrated picture of land-river-ocean interactions. Satellite observations should serve also to enhance in situ studies and should be in place for the unpredictable duration of such studies.

Observations from space-borne platforms should play a pivotal role. Sediment loads and color changes provide a signature for river water, allow for measurement of phytoplankton standing crops, and permit observation of mixing processes and deposition of sediment. As sediment is removed by settling, light penetration increases and phytoplankton blooms appear. There are empirical relationships between the depth of the mixed layer and chlorophyll concentration, which may be measured from space.

Remote sensing of changes in the drainage basin provides essential information relating terrestrial processes to observations in the rivers themselves. Data on the extent of marginal flooding allows extension of pointwise flow data, permitting interpretation of complex hydrographs as required for the major objectives. Observations of large-scale sediment and chlorophyll distributions in estuaries and coastal zones are needed to place in situ data in the larger context envisaged for the global habitability program.

In summary, transport of nutrients and sediments from land to sea via rivers provide a major link in the global cycles of C, N, P and water, yet very little is known concerning the process. River-borne transport plays an important role in nourishing or polluting regionally significant coastal fisheries. Measurements are required for the fluxes of water, sediment and various compounds of carbon, nitrogen, and phosphorous

from the world's major rivers to their respective coastal zones and within coastal wetlands. This flux can also be used as an indicator of the integrated output of dissolved and suspended material from the continents. The measurement program will

require in situ measurements in rivers and shipboard measurements in coastal zones. Satellite observations can provide the larger scale view of river-ocean mixing, phytoplankton population, and changes in drainage basins.