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Global Change: Impacts on Habitability

A Scientific Basis for Assessment

A Report by the Executive Committee of a Workshop held at Woods Hole, Massachusetts, June 21-26, 1982

Submitted on behalf of the Executive Committee on July 7, 1982, by Richard Goody (Chairman)

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Executive Summary

The earth is a planet characterized by change, and has entered a unique epoch when one species, the human race, has achieved the ability to alter its environment on a global scale This report outlines a scientific strategy that would offer a basis for the difficult choices that lie ahead and for the complex decisions that must be made now to protect the integrity of the earth.

NASA could play a central role in this task. The unique perspectives of space observational systems, the ability to manage complex interdisciplinary science programs realized in two decades of planetary exploration, and the overall technical expertise of NASA are essential to the success of the endeavor

This report is directed to issues that arise on a relatively immediate basis: the time horizons of people now alive. We are concerned with matters that relate to the production of food adequate to the needs of a growing population and with subtle interactions that might affect the planet's ability to sustain and renew the quality of air and water and the integrity of the global chemical cycles essential for life. We approach the task in a spirit of optimism, but with a clear recognition of the magnitude of the challenge.

Needs of the past could be met by the expansion of frontiers, by land clearance, by application of chemical fertilizers and pesticides, by irrigation, and by intensive application of energy resources harvested from the sun by the biosphere in years past. Now, however, humanity is being confronted by the finite dimensions of its world. In the twentieth century, humanity has become a factor in the global cycles of carbon, nitrogen, phosphorus, and sulfur and can affect global and regional air quality and climate; even control of the powerful hydrological cycle is within its grasp. An understanding of the overall system is essential if the human race is to live successfully with global change

The magnitude and complexity of the scientific issue are prescribed by the choice of time scale. On time scales of a decade or so, the ocean, atmosphere, and biosphere function as an integrated system. Physical, chemical, and biological processes are coupled, and progress in understanding them will require an interdisciplinary science research program of broad scope and content. Such a program would require space observations to provide a global perspective; investigations of specific ecosystems both on the ground and from space to deepen scientific understanding of the overall function of the biosphere; studies of representative estuarine and coastal systems to define the transfer of materials from land to ocean; studies of horizontal and vertical motions in the ocean, recognizing the importance of these motions for climate and their role in regulating the flow of materials to the depths of the ocean; studies of the atmosphere and its chemistry, physics, and motions; and theoretical and laboratory investigations to synthesize new information and to serve as a guide for acquiring new data.

A group of some 50 scientists, including physicists, chemists, and biologists, met recently at Woods Hole to consider these matters and arrived at the following general conclusions. A program of research can be implemented that would respond to the overall concern regarding the future habitability of the planet. Some elements of the program are already in place or can be carried out with a modest redirection of available scientific, administrative, and financial resources. Other elements can be defined now, while some will require further consideration. The investigation of interconnections between land, ocean, and atmosphere is crucial and the view from space is necessary for integration on a global scale. The task is urgent. Because the human race has reached the point of being able to change the earth significantly on a time scale of mere decades, its ability to mount countermeasures, should it wish to, is restricted in many cases to a time scale that is similar or longer. A commitment by the United States Government is essential to further progress and there is an obvious need for international cooperation. We can see no better use for the mastery of near space than the acquisition of the body of knowledge essential to the future well-being and prosperity of humanity.

Contents

Abstract

This report addresses the feasibility of a major NASA research initiative to document, to understand, and if possible, to predict long-term (5–50 years) global changes that can affect the habitability of the earth. The major factor contributing to change is human activity. The problem is urgent in the sense that situations are already being created that can take decades to reverse. The appropriate science community is available to support such a research program, and the need is urgent for a commitment to proceed by the Federal Government.

The program will involve studies of the atmosphere, oceans, land, the cryosphere, and the biosphere. On decadal time scales, these regimes and the cycles of physical and chemical entities through them are coupled into a single interlocking system Some part of this system can be studied in a straightforward manner (the atmosphere) and some with great difficulty (the biosphere) A new emphasis for NASA would be to design and carry through studies of the complex interactions. A major effort to involve new scientific talent would be necessary, particularly from biology New management approaches by the agency would be required.

The program would be large, comparable in size and scope to other major activities of NASA such as the Physics and Astronomy Program and the Planetary Exploration Program. It would require support for at least a decade. The program would involve international collaboration, although the U.S. initiative should be unambiguous and managerially independent. Space systems would be emphasized, but *in situ* observations would also be required. A large theoretical and laboratory program is essential.

Detailed studies exist of some of the space systems needed to execute this program, e g., the Ocean Topography Experiment, the Upper Atmospheric Research Satellite, and the imaging radar for cryospheric studies. The early funding of such projects and studies of advanced systems is a cornerstone for the ultimate success of the program.

Global Change: Impacts on Habitability

A Scientific Basis for Assessment

I. Introduction

This report responds to a request by the National Aeronautics and Space Administration for the establishment of a group to discuss the viability of a major research initiative in the area of global habitability, specifically addressed to the question of changes, either natural or of human origin, affecting that habitability. The program should be one of research, which we interpreted to mean a concern with the foundations of knowledge needed for enlightened policy decisions. It should be responsive to human needs. It should be urgent in the sense that it needs to be undertaken now, and not in a few years. The changes in habitability discussed should be of significance within a human life span (50 to 100 years), with less emphasis on short terms of a year or two. And finally, we were asked to consider why this program might be appropriate for a NASA initiative.

Following an organizational meeting in April 1982, a workshop was convened for the week of June 21 through 26. Those present at the workshop are listed in the Appendix.

The membership of the workshop covered an unusually wide range of disciplines. We examined science issues and possible research programs to the extent necessary for responsibly answering the basic question: can a program be formulated that responds to the requirements, that could be rationally developed from the theme of global habitability, and that NASA could successfully carry out? We took the discussion to the point of concluding that the answer to the question is "yes," but not to the point of identifying the optimum programs. That step remains to be taken. This paper presents a selection of scientific issues and program elements developed by the executive committee, without any claim to completeness

The responsiveness of the program to human needs and the issue of urgency are discussed in Chapter II. Chapter III discusses some scientific issues concerning the problem of global habitability and Chapter IV discusses some of the programs that could lead to substantial increases of knowledge in the foreseeable future. These two chapters together establish the validity of the program and its feasibility. Here, we will briefly cover some general issues that arose during our discussions.

A research program concerned with changes in global habitability would contain some familiar elements and some that are less familiar. The familiar elements involve current activities in atmospheric, oceanic, and land-surface research The coupling between the ocean and atmosphere for time scales longer than a few years is also a familiar concept, but when we introduce, additionally, biological activity in the sea and on land, the couplings become even more complex. On the decadal time scale the atmosphere, the ocean (the top 500 meters), the biosphere, and the physical properties of the land surface are linked in a fascinating but exasperating symbiosis.

Is it possible to design effective programs for investigating a system of such complexity? Some have argued that analytic approaches are usually simplistic and that, on the other hand, the full complexity is beyond existing comprehension If we were to accept this dichotomy it would be difficult to argue that a program of research appropriate to NASA can be defined. On the contrary, we believe that important aspects of the global problem can usefully be isolated and subsequently integrated into general ecological themes at the appropriate time and space scales. We had no difficulty in identifying major areas in which scientific issues and effective research programs could be formulated. A specific example is the nutrient cycle involving nitrogen, carbon, phosphorus, and sulphur. These elements cycle through the atmosphere, ocean, and land biosphere. We have little certain knowledge about them and productive research programs can be designed. Some aspects of the cycles, e.g., the carbon dioxide problem, have already emerged as stimulating research areas with significant consequences for public policy.

To break the ecological problem down into manageable elements or, alternatively, to emphasize the complexity of the entire system—these represent different approaches that will continually emerge, because both are valid. Their existence, however, emphasizes the need for the highest quality of scientific leadership for NASA's program. Judgments must be made that require scientific credibility and sophistication from both management and the science community. We make no proposals regarding program management, but scientific leadership and the appropriate program structure within NASA are crucial to the success of the program.

While much needs to be done if the program is to succeed, we believe that there is enough strength in some of its parts and enough potential competence in others for a successful outcome. A *sine qua non*, however, is a firm national commitment to a research program in global habitability. Given this commitment and the appropriate leadership, the scientific side of the government–science partnership can be counted upon; but it cannot proceed further without an explicit Federal undertaking to carry through the program for a period of at least one decade.

Why should NASA be responsible for this program? The short answer is that NASA can do it and no other Federal agency can We are proposing a research program that would be global in extent and decadal in time scale. This does not fall fully within the terms of any other single agency. The global character of the problem virtually demands a space capability, and where space systems are not required the problems involve high technology, for which NASA often has appropriate skills. In addition, NASA has no direct operational, service, or regulatory responsibilities, which allows NASA to undertake difficult research programs unimpeded by short-term requirements. NASA has a responsibility for research as part of its mandate under the National Aeronautics and Space Act of 1958. In the pursuit of its responsibilities in space science, NASA has learned how to work with the outside science community as an equal partner. Finally, NASA has experience with interdisciplinary project management of the kind required for this program (Project Viking and the Upper Atmospheric Research Program provide two examples of successful interdisciplinary efforts).

In addition to the appropriateness of the task to the agency, NASA stands to benefit from undertaking it. The agency has developed tools of revolutionary importance for the earth sciences, but the responsibility for the programs has rested with other agencies (the Upper Atmospheric Research Program is the notable exception). This has resulted in split responsibilities that have inhibited the rapid development and utilization of space tools. This contrasts sharply with projects such as Apollo, the Shuttle, and High Energy Astrophysics, for which NASA had overall responsibility, and which were superbly executed. The global habitability program can provide NASA with a mission responsibility in the earth sciences that, properly handled, could lead to outstanding advantages for the earth sciences as a whole.

In summary, our workshop deliberations led us to conclude that a valid program can be developed involving global investigations of changing conditions affecting habitability; and that its development is urgent. We concluded that the long time scales (5 to 50 years) and the global character of the problem define the necessary thrust of the program and that the interactions between land, sea, and air on the one hand, and biology, chemistry, and physical processes on the other, provide some of the crucial aspects of the tasks. We found that a commitment by the Federal Government was essential to further progress and that there are exceptionally difficult questions in science and program management.

It has been suggested from many sides that this program might be announced as a U.S. initiative at Unispace 82 to be held in Vienna in August, 1982. While we are conscious of the great difficulties in effective execution, we nevertheless believe that the step is appropriate for reasons both of feasible science and of good international policy.

II. Impact

The human race lives on a planet characterized by change. Change is evident on all space and time scales, from the very large and very long—the hundreds of millions of years associated with rearrangement of the continents—to the very short and relatively local—the day-to-day variations of weather. This is a unique time, when one species, humanity, has developed the ability to alter its environment on the largest (i.e., global) scale and to do so within the lifetime of an individual species member. This report is concerned specifically with changes that may affect the habitability of the earth: the ability of the planet to support communities of plants and animals, to produce adequate supplies of food, and to sustain and renew the quality of air and water and the integrity of the chemical cycles essential for life.

While life has persisted on the earth for more than 3.5 billion years, its course has been threatened many times during the history of the planet. Volcanic eruptions and advancing ice sheets have altered the temperature and circulation patterns of the atmosphere and ocean, leading to great change in local areas. Species have become extinct and others have evolved to take their place. Most species of animals have survived for periods of the order of 10 million years or so and then disappeared, mainly for reasons related to the destruction of habitat. Food, water, air, and climatic conditions changed gradually but inexorably beyond the ability of species to survive.

The human species faces a similar challenge. In contrast to its less successful predecessors, however, humanity has the ability to manage its resources, to plan intelligently for its future, and to preserve the necessary elements of its habitat. On the other hand, if the human race is to be successful in this endeavor it must take steps now to develop the body of knowledge required to permit wise policy choices in the future. The task is urgent.

Humanity has been accustomed in the past to respond to changes as they occurred: to move to the next valley when local resources were impaired or to substitute energy-intensive technology for the natural course of resource renewal. But the next valley is now occupied. Humanity is being confronted increasingly and rapidly with limitations imposed by the finite nature of its habitat. The human race is now a major direct and indirect influence on the chemistry of the atmosphere and on the allocation of resources on land, and is increasingly an influence on the ocean. That its influence can be subtle is illustrated by recent concerns regarding the potential vulnerability of stratospheric ozone.

It has become apparent within the last decade that humanity has developed the ability to alter ozone and thus to change the level of harmful ultraviolet radiation penetrating to the ground. The direct injection into the stratosphere of the exhaust gases of high-flying aircraft, the release of chlorinated gases used as aerosol propellants, as industrial solvents, and as refrigeration-system working fluids, and the creation of complex perturbations within the global nitrogen cycle can all lead to such a change. However, while these activities lead for the most part to a reduction in ozone, they are offset to some extent by thermal disturbances, due to enhanced levels of carbon dioxide, that cause a rise in ozone. Humanity's assessment of its own impact is hampered by its lack of understanding of the underlying physical, chemical, and biological influences regulating ozone in the natural state, and humanity's assessment is forced to proceed in parallel with a research program designed to provide this fundamental body of knowledge. The matter assumes urgency because the gases responsible for changes in ozone—human-made chlorocarbons and biologically formed nitrous oxide—have lifetimes ranging from 50 to 200 years. The self-cleansing function of the atmosphere proceeds slowly and human effects today will persist for centuries.

Carbon is the largest single waste product of modern society. Humanity has added, by burning fossil fuel, over 100 billion tons of carbon to the atmosphere as carbon dioxide since the industrial revolution, with perhaps a quantity of similar magnitude transferred from the biosphere to the atmosphere over this same period as a consequence of land clearance for agriculture. The increase in the burden of atmospheric carbon dioxide is readily detectable. Approximately half of the carbon added to the system remains in the atmosphere and the remainder is presumed to have been taken up by the ocean and transported to the depths of the oceanic abyss.

Massive engineering programs are being initiated to alter the course of major rivers—Soviet plans for three of the ten largest rivers in the world are an example—the consequences of which on ocean physics and therefore on climate would be continental if not global in scale. The increasing pressure on fisheries from humanity and from atmospheric variability has led to decreases and often elimination of traditional protein sources in many parts of the world. The consequences of chemical change can be detected in the coastal waters of all the developed nations. These are no longer isolated problems; taken together, they affect the habitability of that part of the earth most exposed to population pressures.

Changes brought about by human activity must be monitored and assessed and the science community must be prepared to recommend responses when necessary. Changes involve soil erosion, loss of soil organic matter, desertification, deforestation, overgrazing, diversion of freshwater resources, rising levels of air pollutants, and acid rain. On the decadal time scale, land, sea, and atmosphere operate as a coupled system not only in their physical interactions, but also through chemical and biological processes. Water in the upper layers of the ocean has a residence time of a few decades and the cycling time for carbon and nitrogen through the terrestrial biosphere is on the same scale. Physics cannot be separated from chemistry and biology by considering them consecutively. Nor can problems in the ocean be treated in isolation from those on the land or in the atmosphere. The necessary questions relate to the interaction of land, sea, and atmosphere. Activities on land alter the atmosphere, which in turn affects the physical and chemical dynamics of the ocean. The total effect at decadal time scales depends on the response of the ocean, the flywheel for these interacting components. The habitability of the earth depends not only on the presence of the great mass of water in the ocean, but also on its dynamics. The transport of heat in the ocean helps to determine continental climate; the ocean controls the exchange of water through the hydrological cycle and determines the long-term balance of carbon and other essential chemicals. To understand this total system, the physical dynamics of the upper layers of the ocean and the exchange from these layers to the atmosphere above and the deeper ocean below must first be understood. Then this knowledge must be used to determine the consequences of change upon the chemistry and biology of the whole system.

This program requires greater knowledge of each of the three components—land, sea, and air, on regional to global scales—but the study of their interactions must particularly be emphasized. One such interaction concerns the direct connection between land and sea. Not only is population increasing rapidly, and not only is this increase most marked at the coastlines of all the continents, but also cumulative human-imposed changes in coastal waters are taking the problems beyond their previous terms of reference.

While it has reached the point of affecting the global system significantly within a few decades, humanity's ability to introduce countermeasures, should it wish to, is on the same time scale or longer. There are inherent dangers that must be anticipated when changes are imposed more rapidly than humanity's ability to achieve control. Steps must be taken now to develop the necessary scientific base. In the past the study of global habitability has been scattered among several independent disciplines, such as atmospheric physics, biology, oceanography, etc. The attempt to isolate problems that are tractable is the nature of scientific investigation. As the knowledge in each discipline has grown, so have the boundaries of investigation. We have now reached the point where the boundaries of each discipline are overlapping, and the next step forward can only come from an interdisciplinary research program. Such a program requires dedicated scientists, sophisticated tools using advanced instruments, computer and satellite technology, and strong managerial leadership.

The ultimate goal of the research program proposed here is that it should provide a scientific basis that can aid in policy decisions. It should be stressed that this cannot be put together in a single predictive model. Only studying the natural environment, understanding its varied processes, and showing that this knowledge can be distilled into the form of several comprehensive models will provide confidence in the utility of models for forecasting future events.

Fortunately, through satellites, computers, and modern communications humanity has the scientific tools to carry out the required research. At the same time the theoretical tools have advanced to the point where the integrated study of the global system is becoming feasible. If both are carried forward, the future may be manageable.

III. Some Science Issues

The problem of global habitability leads directly to some of the most interesting and difficult scientific problems that have emerged in recent decades. In this chapter we consider a few of these in order to illustrate our view that their importance is great and that their intrinsic interest is such as to ensure enthusiastic participation by the research community. We should emphasize, however, that we have made no attempt at completeness.

Global changes that impact the earth's habitability are principally of two kinds: those relating to biological productivity and those affecting human health. Both involve the cycling of energy, water, and essential chemicals through the atmosphere, land, and oceans. The problem is complex and interactive. However, it is possible to identify several crucial scientific questions that must be answered before future changes in habitability can be effectively assessed. It is possible also to formulate a program to address them.

Biological productivity over land is paced by the availability of water, nutrients, and light; in the oceans only the latter two are of concern. Changes in the global rainfall distribution, intensity, and timing are critical for land productivity. The flow of nutrients through the rivers to the coastal zone and their eventual mixing with deep ocean water and similar transfers from land to ocean through the atmosphere are dominant factors for productivity in the oceans. The problem of assessing these changes becomes more complicated when it is realized that natural rainfall patterns over the globe are only marginally predictable by current climate models and are now being perturbed by the introduction of optically active gases, which are changing the temperature regime and impacting the evaporation–condensation cycle. At the same time, other chemicals are being added to the atmosphere, changing the acidity of rainfall, the level of toxic gases, and the amounts of nutrients in the soils, rivers, and eventually on the coastal shelves. They may even modify the intensity of near-ultraviolet radiation reaching the earth's surface. The objective then is to isolate the natural variability of biological productivity, and then to assess the impact of human-induced changes in the global system. What needs to be done to get at the problem?

One area of intensive research has to be the investigation of the global hydrological cycle. Many phases of the hydrological cycle, from evaporation and evapotranspiration through the vertical and horizontal transport of water vapor to cloud processes and ultimately to precipitation, are coupled directly to the circulation of the atmosphere and have important dynamic feedback mechanisms. The circulation is interactively linked to the radiation budget through optically active gases or possible changes in the solar flux and to the transport of minor constituent gases, including those that are chemically and biologically active. *It is, therefore, critical that the principal components of the hydrological cycle be thoroughly understood.*

Areas of major uncertainties are evapotranspiration over land, evaporation and precipitation over oceans, and cloud formation and precipitation processes. Scientific understanding of the vital role played by vegetation in the transfer of water from soil to air must be improved and quantified. It is necessary to establish climatological distributions of clouds, precipitation over the oceans, and evaporation from the ocean surface; at the present time the last two are unknown by at least a factor of two.

Habitability questions are particularly sensitive to the variations in global climate. The oceans provide the major regulatory mechanism, particularly on the decadal scales where mixing of the upper few hundred meters acts as the flywheel determining the rates of interaction with the atmosphere. *The oceanic processes that drive this mixing are partly horizontal and partly vertical, and the quantitative understanding of either is currently inadequate.* The horizontal component is related directly to wind stress, fresh-water exchange, and heat budget, and so interacts closely with atmospheric changes. The vertical component regulates the exchange of essential chemicals and organic matter with the very long-term (1,000s of years) deep reservoir; it also determines the exchange of gases, heat, and water through the sea surface. The overall effect on the atmosphere, and hence on climate, is through the net flux of heat and mass through the sea surface, which is closely linked to the underlying transports and is nonuniform over ocean basins and in time. It is necessary to know how changes in ocean circulation alter exchanges with deeper water and how they affect climate.

Another area of almost complete ignorance concerns the interaction between the atmosphere and the land surface. It operates on time scales that range from days to decades and it includes both gradual and abrupt changes. *There is, at present, no quantitative understanding of the coupling between the atmospheric and land systems.* Climatic models assume constant surface properties (albedo, heat capacity, soil moisture, roughness, etc.). The exchange of radiative energy is governed by surface albedo, atmospheric water content, and clouds Transfer of latent heat is governed by soil properties and land cover that may be irreversibly altered from grassland to desert or from forest to farmland. Such changes profoundly alter the surface albedo, roughness, and evapotranspiration, which may lead, in turn, to a change in climate and in the chemical composition of the atmosphere

Another largely unknown factor in the climatic system involves the role of snow and sea ice. Snow has the highest albedo of any material abundant on the earth's surface and its areal extent is more variable than that of any other material. Its presence or absence, therefore, drastically alters the surface radiation budget and, thereby, surface temperature.

Just as snow modifies the albedo of the land, sea ice, which covers up to 10% of the world ocean, drastically modifies the albedo of the surface of the sea. In the "landlocked" north, sea-ice extent doubles in the winter, with the expansion largely occurring in the marginal seas of the subarctic. In the waters surrounding the Antarctic continent the seasonal change in ice extent is much larger. *Science lacks a quantitative understanding of decadal change in global ice extent.*

Sea ice serves as a deformable heat insulating layer of variable thickness. The heat flux through the cracks in the ice (the leads) is two orders of magnitude larger than through the ice itself. The occurrence of sea ice modifies the seasonal temperature cycle, delaying temperature extremes through the release of its latent heat of freezing in the fall and the uptake of heat for melting in the spring.

Finally, sea ice by its very nature is sensitive to small changes in the atmospheric and oceanic heat fluxes, making it a useful indicator of climatic change. This is particularly true in the southern hemisphere where the movement of the pack is unaffected by blocking land masses (for instance at lat. 60° S, a 1° C change in mean air temperature correlates with a 2.5° latitude decrease in maximum ice extent). A comprehensive program for monitoring the cryosphere can illuminate some of the issues in climate change.

Questions about the availability of the nutrients related to biological productivity again involve chemicals that cycle through the atmosphere, land, rivers, coastal zone, and deep ocean. Removal of chemicals and organic matter across the shelf to the deep ocean is a major pathway in the overall cycles of carbon, nitrogen, and phosphorus. Nutrient addition from rivers is an increasing factor in shelf productivity and it is influenced by human activities The open ocean contributes significantly to the nutrient balance on the shelf and changes in ocean circulation can also alter this balance. The shelf is a direct source of food for humanity and pressures on this supply are increasing rapidly. The mechanisms and processes that control the transport of these nutrients from terrestrial sources to oceanic "sinks" are known only in the most qualitative way. *It is therefore critical to assess the fate of this excess anthropogenic nitrogen to determine its impact on the shelves and coastal zones and ultimately its effect on the rate of fixation of carbon in the open ocean.*

At decadal scales ocean dynamics are inhomogeneous within and between basins. There is an intimate relation between ocean circulation and biological production. *The scientific focus could be on the longer term consequences of these interactions between physical and biological processes in the oceans.* The consequences occur through the exchange of essential or critical elements such as nitrogen and carbon through intermediate depths (300 to 500 meters). These exchange rates can be measured through specific experiments. To generalize these results, however, the processes must be linked to the general circulation and productivity of the upper layers.

How do variations in vertical processes alter the rates of biological and chemical cycles? These changes are driven by mixing over much of the ocean interior. In certain regions, where there is significant net upward or downward movement, the chemical and biological changes are magnified and can play a dominant role in the total exchange; for example, the removal of excess carbon dioxide from the atmosphere probably involves downwelling in the Norwegian Sea. How do changes in upwelling regions affect both regional fish production and global chemical cycles? How are downwelling rates in the high latitudes affected by changes in the general circulation and how, in turn, will these affect the global balance of radiatively important gases? These are some of the questions that need to be addressed on a global scale.

The cycling of carbon, nitrogen, and sulfur through the atmosphere is controlled mainly by photochemical transformations in the troposphere. The sink processes, which include wet and dry deposition and takeup by vegetation, can have important and widespread effects on biospheric productivity, positive in some cases (deposition of sulfur and nitrogen in nutrient states) and negative in others (excessively acidic rainfall with attendant growth reduction and increases in exposure of vegetation to ozone, SO_x, and NO_x). Accompanying the major effects of global atmospheric chemistry on biological productivity are other changes in the atmosphere such as visibility degradation.

Although the exact details of the global carbon, nitrogen, and sulfur atmospheric chemical cycles are far from understood, some key issues are clearly defined. The major challenge in understanding both nutrient (carbon, nitrogen, and sulfur) and toxic (ozone, SO_x, and NO_x) atmospheric chemistry is *to determine the concentration distributions of these materials in the atmosphere, understand the relevant atmospheric transformations, and delineate human inputs from natural sources.*

There is a need to identify natural and human sources of hydrocarbons and to understand the relevant oxidation mechanisms. Regional to global changes in the hydroxyl and ozone concentrations are very important in determining the pace of photochemical cycles. Tropospheric ozone appears to be increasing not only in polluted air but in "clean air" regions of the troposphere. *It is critical to determine the spatial variation in the concentration of tropospheric ozone and other toxic gases remote from industrial sources*, especially over agricultural and vegetated regions, so as to isolate the effects on primary productivity.

The concern about human effects on stratospheric ozone has been mentioned earlier and represents an important example of a widely recognized issue impacting global habitability. An extensive effort is underway to improve scientific understanding of the chemical and dynamical influences regulating ozone in both natural and perturbed states. The program recognizes the importance of microbial reactions in mediating the concentrations of gases such as methane, nitrous oxide, and various halocarbons and their effects on ozone.

A major scientific issue related to biological productivity and the carbon cycle is that the total biomass of the earth's surface is unknown to better than a factor of two and that the extent to which the biomass changes in decadal time scales is also not known. Complicating the issue is the fact that human disturbances of natural ecosystems over the last 100 years, including the clearing of forests for agriculture, have changed the vegetation and soil reservoirs by relatively large amounts. Better estimates of both the total biomass on the earth's surface and rate at which it is changing are needed before an understanding can be achieved of *how the primary productivity of the earth's surface is being altered by changes in land use, in climate, and in the supply of nutrients.* A concerted program using current capabilities for space and ground observation, especially in tropical countries, can be mounted in order to provide information on the extent of biomass change. This program, with related definitions of changing nutrient cycles, climate, and available energies, can help bring about progress in understanding several areas: the global carbon cycle; the interdependence of carbon with the cycles of other nutrients; the recovery time of the earth's biosphere after a major perturbation; and the reasons for the changing productivity of the semiarid regions.

The scientific issues raised here are not all-encompassing. They provide an example of the range of issues that must be addressed in a program of research motivated by the question of habitability. The scientific expertise is available and rapid progress can be expected in most areas. In others, the challenge is more formidable, and success will require imaginative combinations of talents from different disciplines. The program outlined in the next chapter shows the extent to which this may be achieved.

IV. Some Program Elements

A new emphasis that appears in the global habitability program is on the interaction between land, ocean, and atmospheric processes, with biological processes on land and in the sea as a central concern. Programs can be identified that can contribute to the solution of most of the problems posed in Chapter III. Some are already in existence (e.g., weather and climate), but for the most part these are missions of other agencies and are funded at relatively low levels. Some are ready for execution, such as the Upper Atmospheric Research Satellite and the Ocean Topography Experiment (TOPEX), and they must be funded immediately if a global habitability program is to have meaning. Finally, there are programs, particularly in the biological area, that may be feasible but for which even advanced planning does not exist.

We discuss, in this chapter, only a few of the possible programs, with emphasis on those that involve interactions between disciplines. This is where innovative and interesting new approaches are possible, but it should be borne in mind that many of NASA's existing programs are also crucial for the successful execution of a global habitability research program.

A NASA research program cannot concern itself with space systems alone. In each of the following sections, therefore, we indicate the activities required for global observations, for process studies (laboratory research, ground-based measurements), and for theoretical research.

The Atmosphere

NASA already has a well-conceived and productive program in stratospheric chemistry research, mandated by Congress in 1976. The focus of this program is on understanding the stability of the upper-atmospheric ozone layer and on examining changes or threats posed by human activity.

A key new element in the upper-atmosphere program is the Upper Atmospheric Research Satellite (UARS), planned for launch in 1988, which will study the coupling between radiation, chemistry, and dynamics. An integrated program involves sets of global UARS satellite measurements, *in situ* field measurements utilizing aircraft and balloon measurements, laboratory studies, data analysis, and theoretical work (for details see JPL Publication 78-54, *Upper Atmosphere Research Satellite System*).

A tropospheric research program, more extensive than that which NASA now has, needs to be developed. The immediate aim would be to provide global data and parameterizations of physical processes for incorporation in numerical models of hydrological and biogeochemical cycles. These models are not ends in themselves: they cannot substitute for careful thought and understanding, but they are helpful in providing guidance to the important measurements and to the required precision of measurement.

One physical process that is inadequately understood is that of cloud formation and its influence on the planetary radiation fields. We have yet to document cloud climatology on a global scale, a task well-suited to earth-orbiting systems. A large program has been proposed to take place from 1983 to 1988 under the auspices of the World Climate Research Program (see *International Satellite Cloud Climatology Project (ISCCP): Preliminary Implementative Plan*, ICSU/WMO, January 1982). NASA can and should be a major participant in this program. The agency should also undertake detailed cloud and precipitation process studies using aircraft for observation platforms.

Knowledge of tropospheric chemistry lags behind stratospheric chemistry and, at this time, the need is for measurements, from aircraft, over the full tropospheric altitude range and over a range of conditions of the concentration (or flux if possible) of carbon dioxide, carbon monoxide, methane and other hydrocarbons, ozone, ammonia, chlorofluoromethanes, SO_x, NO_x, hydroxyl, aerosols, and other species. Laboratory and field measurement techniques need to be developed for these studies. Global measurements from space will eventually be required to provide a data base for global tropospheric models.

The Ocean

Global measurements from space are ideally suited for providing improved understanding of the ocean's large-scale, low-frequency circulation, but such measurements are inherently limited to features at or near the sea surface. Of prime importance are measurements made from space of sea-surface elevation and global wind stress, with complementary measurements made within the ocean. A global program combining subsurface measurements with those from satellites can best be accomplished by transmitting *in situ* data directly to one or more satellites.

The United States has pioneered in the field of ocean observations from space, and NASA must maintain an active program in those aspects relevant to its concerns with global habitability. NASA is ready to proceed with an ocean topographic satellite (TOPEX), which can greatly increase knowledge of the transport of heat and chemical species in the oceans. The funding of this program is an early order of business.

The need to unify space and *in situ* measurements is particularly pressing in oceanic research. A valuable and distinctive character could be given to the U.S. program by making a major effort to integrate NASA's activities with those of the oceanographic community, with its tried *in situ* methods. An immediate commitment by NASA to space oceanographic missions is essential if the interest and involvement of U.S oceanographers is to be increased above its current low level.

Further steps concerned with research into the close coupling between the atmosphere and ocean are under active consideration by many international groups. The United States should participate in their efforts and collaborate in program execution. Current planning by the Joint Scientific Committee of the World Climate Research Program involves:

- A "Cage Experiment" to address the problem of estimating the annual mean surface heat flux to the atmosphere on an ocean-basin scale.
- A "World Ocean Circulation Experiment" to address the problem of estimating the rate of bottom water formation and to determine the dynamics of the slow, large-scale components of the ocean circulation.
- An "Interannual Variability of the Tropical Oceans" program.

These programs fit, to varying degrees, within the objectives of a global habitability program, and all contain major space elements.

An ocean biological productivity program should focus on one major theme: the exchange of major chemicals between near-surface and deeper water. Distinctive regions are the open ocean, centers of upwelling and downwelling, and the coastal zone; each has markedly differing vertical exchange processes. The aim should be to determine physical and chemical conditions and rates of biological processes from *in situ* measurements, so that the information can be used together with remote sensing data to extend scientific ideas in space and time. Physical programs to measure advection and diffusion should be closely linked with measurements and experiments on dissolved and particulate constituents. A key requirement for assessing the net long-term rates of removal of carbon, nitrogen, and phosphorus from the system is the measurement of sediment and organic matter at the shelf edge prior to removal. New instrumentation for this purpose is needed. To connect the physical changes with net chemical transports the basic biological dynamics that link these components must be understood. Several focused experiments to study ocean productivity are outlined in the *Satellite Ocean Color Science Working Group Report* (NASA, 1982) These include river-dominated, wind-upwelling, western-boundary, and open-sea experiments.

The Cryosphere

It is currently possible to measure snow extent using satellite imagery, but it is not possible to obtain by remote sensing other physical data (depth, density, water equivalence, free-water content, age, crystal size, type, etc.). Recent studies of microwave systems have shown promise, and work should be initiated on systems to extend scientific understanding of processes occurring within natural snowpacks.

The situation for sea ice is different in that there are a number of sensor systems that have proven capabilities. The most valuable of these operate in the microwave range and are not limited by either clouds or the absence of light. Of particular value is synthetic aperture radar, which supplies high-spatial-resolution information on ice extent, type, and roughness in a map-like format. Also of value are passive microwave radiometers (low-spatial-resolution information on ice extent and type), radar altimeters (ice extent and topography), and scatterometers (ice extent, type, and surface roughness). In short, the sensors are available; it is their deployment into suitable orbits and the utilization of available data that have lagged behind.

Cryospheric research is an area of central importance to the coupling of the ocean and the atmosphere. Several international and national programs are in progress or under discussion. The role of space observations is crucial, and important contributions are described in documents such as *Guideline for the Cryospheric Processes Special Study*, (NASA, 1982). And yet, no synthetic aperture radar or other innovative measurement has been authorized by the United States. Again, the ground for a global-habitability thrust is thoroughly prepared.

The Land

We have identified the crucial importance of biology to processes in the atmosphere and the ocean on the decadal time scale; the reaction of global processes upon the biosphere in turn is not only the return path in a fully interacting system, but, in addition, defines the social issue of importance to this study More than 90% of the global biomass is on or in the land surface but, despite the fact that humanity exists in close contact with it and deploys considerable effort on agricultural and ecological research, there are too few available data for allowing generalizations regarding the global system and no demonstrated concepts upon which a large measurement program can be based.

If resources are devoted, as they should be, to a global habitability program, the greatest single need is to broaden the intellectual base in the area of land biology and to evolve, virtually from first principles, useful measurements addressed to the problems raised in Chapter III.

There is only limited experience to draw on. Landsat images have yielded some interesting details, but there is no substantial reason to suppose that land biomass and its changes (let alone soil biomass) can be reliably measured, on a global scale, with any similar system.

Studies have been made of space systems for measuring soil moisture. There are some reasons for encouragement here, but there is a long path to travel before a credible program can emerge (JPL Publication 80-57, *Joint Microwave and Infrared Studies for Soil Moisture Determination*).

Studies of small ecosystems, monocultures, and other activities evolving from chemical studies make continual progress, but they are difficult to relate, with confidence, to global questions. Presumably, enough studies in enough detail would provide some insight, but this only shifts the burden to the need for an intellectual synthesis of extraordinary difficulty.

What achievement, then, can be hoped for in this area? The distribution of land biomass and its natural and human-induced changes are primary targets for investigation. Further efforts to use Landsat data in a quantitative fashion and attempts to define more sophisticated measuring systems should continue.

Studies of new concepts in remote sensing, e.g., to measure soil moisture, should also continue. The existing effort needs to be accelerated. Where the connection with global change can be clearly demonstrated, studies of individual ecosystems should be undertaken. Studies of toxicity can define the significant tropospheric chemical parameters.

Generally speaking, the present choices for a directed program are severely limited, but we believe that they can be increased in number and their quality improved. The key is an able scientific community and the key to that, in turn, is an agency commitment to the task. In the short term there are, fortunately, many related areas in oceanic and atmospheric research where progress towards the overall goal is possible.

The parameterization of surface data to define thermal and moisture fluxes into the atmosphere for global dynamical models is an area for which a feasible program exists. Aircraft and *in situ* studies can be defined that can determine thermal and transpiration boundary conditions for large ecosystems identifiable from space images. If this is successful, one of the most important links between human activities and climatic change may be understood in quantitative terms.

The Sun

Solar radiation at wavelengths less than 350 nanometers controls the production and destruction of important stratospheric and mesospheric chemical species. Changes in the solar ultraviolet spectral distribution can therefore change the vertical temperature and species profiles in this region of the atmosphere, which may, in turn, change stratospheric circulation patterns.

In the ultraviolet region, intensity variations of several percent have been measured over a period of a single solar rotation. Because of unsatisfactory calibrations in the past, science does not yet have a long-term data set of solar spectral variability. Instrumentation suitable to the task has now been developed for periodic Shuttle flights.

In terms of the total energy from the sun falling on the earth, only recently have direct measurements become available with sufficient accuracy to establish the reality of solar variations. These indicate changes over a few days on the order of a few parts per thousand; small on the scale of phenomena that may affect habitability of the earth.

Changes of a few percent would, however, be important, and a long time series of measurements is required to establish whether they occur. As a minimum, the total solar irradiance should be measured over a full solar magnetic cycle to a precision of 0.05 percent or better.

Interactions

Many of the most interesting and least understood features of the global system concern the interactions between land, sea, air, and life. In this section a few out of many possible research directions concerning interactions are discussed.

For the hydrological cycle, NASA already has several active programs, but the balance between evaporation and precipitation over the oceans is a neglected area. A combination of infrared and microwave sounders with active and passive techniques for determining surface stress offers some promise of yielding data on evaporation. Precipitation can possibly be inferred from cloud forms and from altitudes of cumuliform clouds and from radar reflectivities for stratiform clouds. A directed thrust to determine evaporation and precipitation over the oceans appears to be justified.

The cycling of carbon, nitrogen, and sulfur across land, sea, and air boundaries is a central problem. Some information comes from tropospheric chemical measurements, but the more difficult features require *in situ* and aircraft measurements. It is necessary to know more about microbiological activity, reservoirs of relevant species in the three media, and transport between them, and it is necessary to integrate this knowledge with coupled numerical models. Many aspects of this problem are feasible now.

Another surface chemical problem concerns the destruction of ozone at the land and sea surface. We have signaled the importance of ground-level ozone but heterogeneous destruction at the surface is poorly understood and a program of research could be designed.

Sensible heat fluxes at the ocean surface are required, together with water fluxes, to define the heat transports in both the ocean and the atmosphere. This important parameter can be obtained from infrared and microwave space soundings under certain conditions, and a more active program should be undertaken.

The problem of desertification is one of interactions. We have discussed the evapotranspiration cycle, and steps that could be taken to further understand it. But what conditions led to irreversible changes on the land, perhaps even to the decay of earlier civilizations? Space tools can, at the least, provide the monitoring of patterns of changing land use. As the physical understanding of desertification increases, observational tools can probably be devised to provide the needed data.

Interactions between land surfaces and the oceans over decadal time scales are changed primarily through runoff. Runoff provides a means for removal of chemical species and organic matter from land and is the major source of fresh water to the oceans A general survey is required for several select estuarine systems and coastal environs to trace export of various chemicals and organic matter from the terrestrial source to the long-term oceanic sink and to establish a flow data set from which induced changes can be assessed. These are, principally, *in situ* studies, but attempts must be made to relate to measurements by color scanners and other space observations.

Studies need to be undertaken to understand how changes in biochemical transports and the quantity of fresh water affect coastal productivity. A mixture of space and *in situ* measurements here is essential to obtain a full representation in both space and time.

Data Sets

Much has been written on the extraordinarily difficult problems involved in handling global data sets so that they are useful for the purpose for which they were gathered. It is often simpler to collect data than to use it. Examples of the destruction of unique information for apparently extraneous reasons are growing. The problem will not look after itself but requires a directed activity of high priority.

The nature of the problem is discussed in *Guidelines for the Air-Sea Interaction Special Study* (JPL Publication 80-8, 1980), and a strategy is proposed around the following conceptual elements:

- Understanding satellite signals.
- Instrument verification.
- Combining the capabilities of several different remote sensors with remote and *in situ* capabilities to measure a given variable.
- Utilizing a directly sensed remote measurement as index of a climate change.
- Comprehensive data management to provide an easily usable data base.

Each appears deceptively simple, but requires, in practice, a major effort.

V. National and International Considerations

National Programs

There is no national research program of the same overall scope as that proposed in this report. However, the United States does have scientific programs and operational systems that encompass elements of the proposed program—e.g., the National Climate Program. NASA can work with other agencies and with industrial users through existing relationships in order to make its data and findings available where needed.

The International Aspects

A global habitability program must be international in scope and requires the cooperation of the international science community. No one nation could carry it out alone. These considerations are recognized by scientists and policymakers around the world.

There are many areas of possible collaboration in different geographical regions at different levels of effort. Such areas could, for example, include ground-based measurements of major estuaries, coastal shelves, tropical forests, and oceanic upwelling regions.

The Global Atmospheric Research Program is a good example of an enterprise that has achieved effective international cooperation between large and small nations in its planning, its realization of the required observational system, its resource allocation, and its analysis and interpretation of results.

Other International Programs

The major international programs relevant to the proposed global habitability program fall under the auspices of the United Nations Environmental Program (UNEP), the World Meteorological Organization (WMO), the International Council of Scientific Unions (ICSU), and the United Nations Food and Agriculture Organization (FAO). Although their definition and coordination are carried out by the appropriate international bodies, these programs rely for their execution on national agencies and resources and on scientists in individual countries.

Examples of these programs, all of which are supported by the United States, are:

- The Global Environmental Monitoring Systems, which are concerned with monitoring a variety of environmental factors and are a part of Earthwatch, a program coordinated by UNEP.
- The World Climate Program, with two major subprograms: an Impact Program, which is the responsibility of UNEP and assesses the impact of possible climatic changes on human activities such as agriculture, water-supply, etc., and a Research Program, which is the joint responsibility of WMO and ICSU and aims to acquire scientific understanding of the climatic system.
- The Middle Atmosphere Program of ICSU, which aims to observe and understand the middle atmosphere, especially the ozone layer.
- The global agricultural productivity activities of the FAO, which include the regional desert locust project and soil-information and crop-statistic planning-assistance efforts.
- The Consultative Group on International Agricultural Research, which coordinates the research in some fifteen international research centers located in various countries, mostly in the developing world.

International Collaboration

To ensure effective global collaboration, NASA can:

- Encourage and invite participation in the U S. programs of experimenters from all countries, to develop instrumentation, acquire comparative observations to corroborate satellite-obtained information, and analyze and interpret data.
- Contribute to the environmental research efforts of WMO, FAO, UNEP, and other regional and international agencies. NASA can correlate its research with the research aims of these bodies and can engage in data exchange, cosponsorship of specific projects, and joint efforts to publicize results and prognoses.
- Consult with and coordinate its plans with other satellite-operating agencies.

Appendix

List of workshop attendees, 21 – 26 June, Woods Hole, Massachusetts

Executive Committee

Richard Goody (Chairman)
Robert Chase (Executive Officer)
Wesley Huntress (Executive Officer)
Moustafa Chahine
Michael McElroy
Ichtiaque Rasool
John Steele
Shelby Tilford (NASA Representative)

Attendees

James Baker
Victor Baker
William Bishop
Harry Blaney III
Daniel Botkin
Geoffrey Briggs
Wallace Broecker
Kenneth Carder
Philip Chandler
Kenneth Coughlin
Paul Crutzen
Robert Duce
Peter Eagleson
James Hansen
Robert Harriss
Howard Hogg
Donald Hornig
John Houghton
Robert Hudson
James Lawless
Robert MacDonald
Robert McNeal
Lynn Margulis
Berrien Moore
Robert Murphy
James Pollack
Ronald Prinn
V. Ramanathan
Mitchell Rambler
William Raney
Charles Robinove
Robert Schiffer
Brent Smith
Gerald Soffen
Vern Soumi
John Theon
John Walsh
Richard Waring
Robert Watson
Wilford Weeks
Sylvan Wittwer