NASA Conference Publication 2109

Remote Sensing and Problems of the Hydrosphere

Proceedings of a workshop held at
Warner Springs, California
January 29-31, 1979

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Remote Sensing and Problems of the Hydrosphere

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I. FOREWORD

Most environmental scientists are unfamiliar with the capabilities of remote sensing. In a complementary mood, most space scientists are unaware of the substantial unsolved problems facing environmental scientists. The workers in both areas have increased dramatically in the past decade; the definable concerns and technologies have shown parallel changes. With this background, many of us felt an urgency that representatives of both communities be brought together to initiate discussions which might lead to joint research projects. Hopefully, the deliberations would yield insights to increase our knowledges about our surroundings as unexpected and as rewarding as the snow that fell in Southern California at Warner Springs during the Workshop period of January 29-31, 1979.

The focus of the Workshop on freshwater, marine, and atmospheric systems was broad; the problem areas discussed were restricted due to the limited number of participants. Clearly, many important environmental problems were overlooked. On the other hand, both space and environmental scientists sensed that their abilities could readily be extended into the programs that were considered.

This Workshop was sponsored by the NASA Langley Research Center Environmental Quality Projects Office and NASA Headquarters Office of Space and Terrestrial Applications. Participants are listed in the appendix of this publication. The participants were organized into four working groups: Bioprocesses, Gas and Aerosol Fluxes, Particle Fluxes to the Aquatic Environment, and Global Geochemical Problems. The results from the working group deliberations are summarized in this volume.

There is a need for more such workshops. The 3 days at Warner Springs should become a springboard for further dialogues.

Edward D. Goldberg
Workshop Chairman

II. BIOPROCESSES

A. Overview

Aquatic science has arrived at a stage where many of the significant problems which can be attacked with point-sampling from ships or with fixed moorings have been solved or have been taken as far as is practical with presently available technology. Many problems of interest lie in the microscale and macroscale lengths where additional data are needed to direct surface sampling or to augment data collection from ships. It is important to locate physical and biological features of interest so that ships can be directed to, and held within, the geographical areas where the features occur. In order to follow time scales of processes which may occur over months or years, we need temporally sequenced sampling over periods of time longer than we can afford to keep ships within features of interest. We need synoptic measurement of physical and biological variables which occur over spatial extents greater than can be sampled from ships within the time frame of the dynamics of the processes and within the cost boundary conditions associated with research vessel operations.

We frequently observe that the limnologists and oceanographers interested in similar biological problems do not pay much attention to each other's literature. Although the problems of each system are similar in terms of biological processes such as primary productivity, transfer of energy to secondary productivity, and fish production, the spatial scales over which the processes operate and the forcing variable types and magnitudes are different. For example, limnologists are greatly concerned with runoff from land as a source of nutrients for lakes. Benthic regeneration and influences of winds may be of secondary importance while tides do not, in general, affect bioprocesses in lacustrine systems. In the sea, winds and tides are of major significance in driving marine food web dynamics. The large amounts of money spent for research in upwelling systems, where half the world's marine fish are caught (ref. 1), are an indication of the significance of wind-forcing in marine systems. Oceanic fronts are now receiving the attention of biological, physical, and chemical oceanographers since fronts are focal points for marine food web dynamics leading to fish production on continental shelves (ref. 2). Upwelling systems extend for hundreds of kilometers along eastern boundaries of the world's oceans (ref. 3) while fronts extend for lengths of from hundreds to thousands of kilometers along various continental shelves (ref. 4). Few lakes possess features of this length scale as the primary forcing mechanisms for biological dynamics.

An additional consideration is the relative importance of various nutrients in freshwater and in seawater. Phosphorus is generally accepted as the leading nutrient which controls phytoplankton biomass in pristine freshwater lakes, a consequence of high insolubility of phosphate-containing minerals and adsorption of phosphate by clays as water flows into lakes (ref. 5). Nitrogen is considered the leading variable which controls phytoplankton biomass in marine waters due to rapid recycling of phosphorus relative to nitrogen (ref. 6). Therefore, limnologists have concentrated their efforts on understanding and measuring phosphorus dynamics and concentrations while oceanographers have concentrated on the nitrogen cycle. As a consequence of both primary and secondary differences in nutrient control between fresh and salt water, phytoplankton of importance for food webs can be different in lakes compared with estuaries and ocean waters.

Since there are similarities in problems remaining to be solved in both freshwater and saltwater systems, the Bioprocesses working group first identified a set of problems of general interest (table 1). We identified a set of parameters which might prove useful in defining remote sensing requirements for aquatic systems. Sensitivity levels (preliminary only) were estimated for each of the parameters for different scales of lengths and for different problems (table 2).

There are important differences in time and space scales of sources, sinks, and forcing variables as well as in the dynamic interaction of system variables between freshwater and saltwater systems (fig. 1). Because of these differences, the working group participants were divided into investigators primarily interested in saltwater and investigators primarily interested in freshwater in order to consider specific problems within the context of freshwater and marine systems.

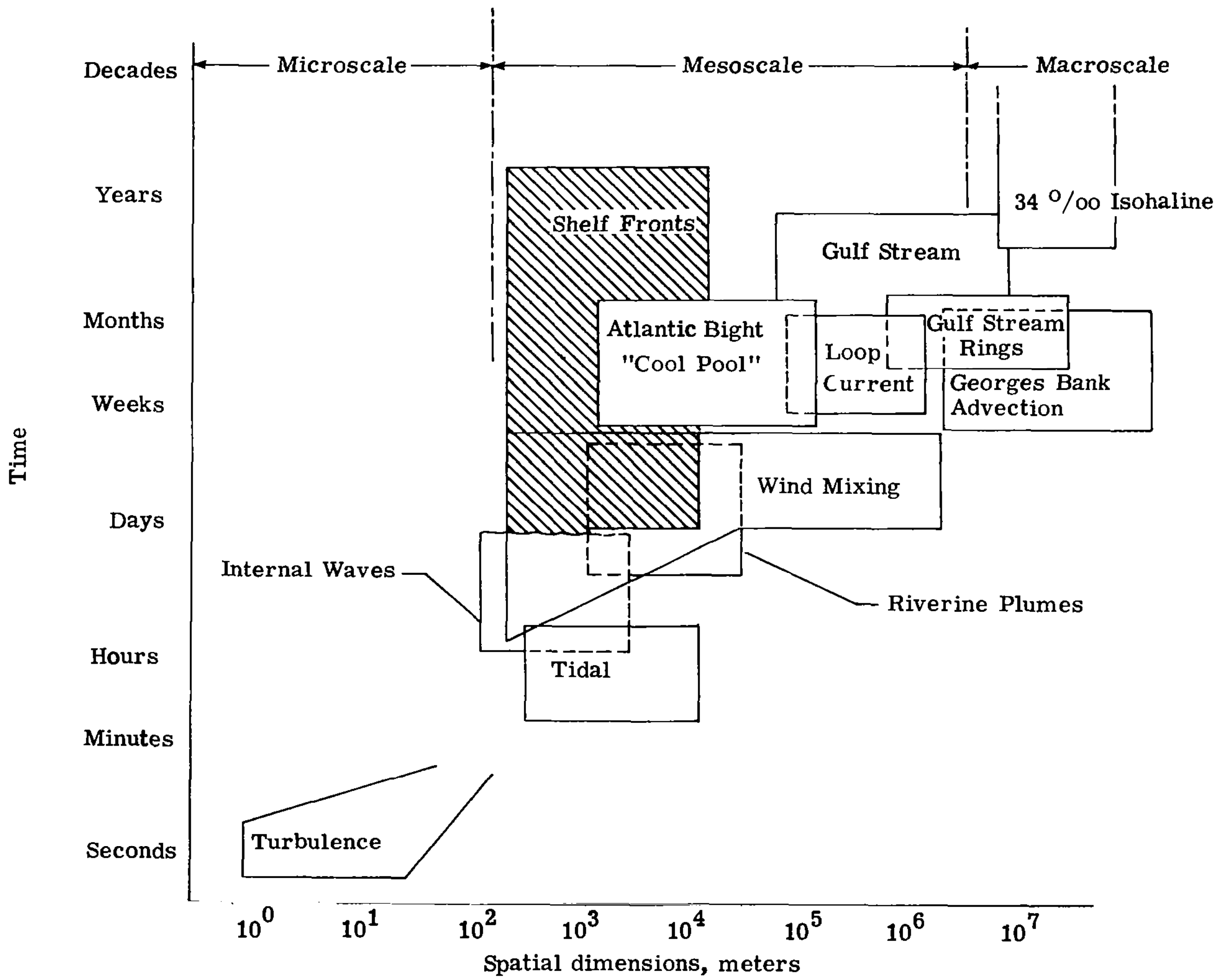

Figure 1.- Bioprocesses' time and spatial scales.

TABLE 1.- BIOPROCESS PROBLEMS: WATER

Sources of water to different parts of the coastal zone
Plumes of all types; location, physical and biological dynamics
Identification of mesoscale and large-scale circulation patterns and how they impact on biological systems
Measurement of rate of change of variables from segmental static observations
Factors leading to patchiness of variables in water
Patchiness identification: source, trajectories
Chlorophyll distribution: in space and time; layer formation
Horizontal and vertical temperature and salinity distributions: synoptic sampling
Pycnocline and mixed layer depths and dynamics
Real-time location of features to guide surface sampling: use of remote tools
Eulerian versus Lagrangian sampling criteria development
Spatial distribution of variables (3-D) for verification of simulation models
Distribution of rooted and floating macrophytes
Dynamics of the coastal boundary layer
Interaction of open ocean with coastal waters
Vertical migrations of zooplankton and fish
Circulation effects on geochemical cycles in the coastal zone
Location of fishing effort via boats; inference of fishing effort hence inference of productivity
Location of fish schools and fish migration patterns
Fish behavior identification: attraction/avoidance with respect to natural and eutrophic features
Assessment of size, species of fish stocks
Measurement of fish recruitment rates

TABLE 1.- Concluded

Diatoms versus blue-greens as indicators of pollution

Assessment of large-scale phytoplankton distribution and productivity

Effects of zooplankton grazing on phytoplankton

Eutrophic effects of species diversity of phytoplankton, zooplankton, fish, animals

Measurement of synoptic nutrient concentration fields: nitrogen (N), phosphorus (P), sulfur (S), metals, organic chelators

Measurement of rate of input of nutrients

Suspended solid distribution and dynamics as nutrient source in estuaries and nearshore environment

Mapping of watersheds including soil types, plant species, rate of waterflow to determine nutrient loading to water bodies

Where does N which drives shelf productivity come from?
Is N the most important variable controlling productivity in coastal zones?

Define criteria for effectiveness of different sewage treatment programs in terms of eutrophication impacts

Distribution of bottom sediment types and nutrient flux from sediments

Nutrient sources, sinks, distribution

Limited cycles versus global cycles of nutrients

Evaporation versus precipitation rates

Coastal fronts: short-term high resolution processes of physics which drive biological processes; rate of large-scale ocean fronts versus coastal fronts

Impact of estuaries on adjacent coastal zone biology, O_2, chemistry

Abundance and distribution of gelatinous zooplankton

Are food chains controlled by average conditions or events?

TABLE 2.- ESTIMATED SENSITIVITY LEVELS FOR VARIOUS PARAMETERS

Aquatic systems	Temperature, °C	Salinity, percent	Current, cm/sec	Wind, m/sec	ρ, Ne $\Delta\rho$	Suspended matter, mg/l	Extinction coefficient, m^{-1}	Nutrients, µg atom/l	Chlorophyll a, mg/m^3	Sea state, m	Particle size distribution
Front location	0.5-1.5	0.5-2	5	4	0.001	0.1	0.02-0.1	NA	0.05-1	0.5	$\frac{1}{2}$ $\log_{10}$
Source sink	0.1	.05	5	2	.001	.05	0.02	N, S 0.05-0.1 P 0.2-0.5	.05	.5	0.5-500 µm
Fish/food web	.1	.5	3	2	.001	1	.1	NA	.05-1	.5	0.2 µm-30 m
Plankton dynamics	1	1	10	3	.001	.05	0.1-0.2	N, S 0.05-0.1 P 0.2-0.5	.05-1	NA	0.2 µm-20 mm (±50%)
*Small Δ *Large Δ	0.1-0.5	0.02-0.5	5 (±10°)	2-4	.001	0.01-0.1 0.1-1	0.01-0.02 0.1-0.2	N, S 0.05-0.1 P 0.2-0.5	0.2-0.5 $\log_{10}$ C	.5	$\frac{1}{4}$ $\log_{10}$ steps $\frac{1}{2}$ $\log_{10}$ steps

*Small Δ refers to small-scale gradients (in terms of strength of physical, biological, and chemical signals); large Δ refers to large-scale gradients. The Δ's were specified first; the other categories were extracted to fit specific problem areas.

A similar pattern of problem areas was independently elaborated by each of the two subgroups of investigators. There is a need for -

(1) Real-time guidance in placement of ships in local areas of intense physical and biological dynamics which we know exist but which occur on such a small scale that large amounts of expensive ship time are required to locate areas before they can be studied.

(2) A characterization of spatial variability in factors such as nonpoint-source input of nutrients to water bodies, biomass of plants (both rooted and floating macrophytes and phytoplankton), and biomass (numbers of fishes and animals require synoptic measurement). An assessment of the effect of changes in sources (space and time) of nutrient and particulate materials is needed not only for management purposes, but also for attempts to verify simulation models used to describe (predict) biological dynamics in aquatic systems.

(3) A characterization of the trophic state of different systems from the standpoint of transfer of energy through the food web. A characterization of effects of catastrophic events such as fish kills or blooms of noxious algae is of interest both for management and for scientific reasons.

B. Freshwater Systems

1. Classification of Lakes: Trophic Characterization, Assessment, and Monitoring. Eutrophication may be defined as an enrichment process which occurs in natural waters and artificial reservoirs. It occurs both naturally and as a result of human activities. Frequently, at least when carried out to an extreme, certain manifestations of the process occur (e.g., dense algal blooms, anoxic conditions, obnoxious odors), making the water body a less useful natural resource. There are tens of thousands of lakes in the United States. They range in size from the Great Lakes down to bodies measuring but a few hectares. Both their large number and vast size, in some cases, as well as their geographic dispersion make trophic characterization and classification a major undertaking. When a national viewpoint is taken, many questions arise. For example:

(1) How many lakes are in the United States?

(2) Where are they located?

(3) How large is each? Morphometry?

(4) What is the trophic status of each lake?

(5) What impact are human activities having on water quality? Point source impact? Nonpoint source impact?

(6) If the water quality is high, what, if any, action can or should be taken to maintain it?

(7) If the water quality is low (e.g., dense algal blooms, high turbidity), what, if any, action can be taken to improve the water quality?

(8) What is the natural variability of lake water quality parameters?

(9) What are the key parameters which accurately, yet cost effectively, characterize lake trophic state?

As a first step, it is necessary to characterize the condition of each water body. This requires that a variety of biological, chemical, and physical parameters be measured; the exact number and kinds are subject to a variety of considerations and is an area in need of further research. The acquisition of the data necessary for trophic characterization and classification is a relatively simple task when only a few small water bodies are under consideration. Traditional approaches are not effective in terms of time and cost when very large lakes and large numbers of lakes are involved. As a result of this dilemma, large-scale research has been impeded because of the lack of a uniform data base.

The problem of characterizing and classifying large numbers of lakes is directly relevant to national goals. Public Law 92-500, the Federal Water Pollution Control Act Amendments of 1972 (Section 314) as amended in 1977, requires that each State shall prepare or establish and submit to the EPA Administrator for his approval:

(1) An identification and classification according to eutrophic conditions of all publicly owned freshwater lakes in such State

(2) Procedures, processes, and methods (including land use requirements) to control sources of pollution of such lakes

(3) Methods and procedures, in conjunction with appropriate federal agencies, to restore the quality of such lakes.

In the July 10, 1978, Federal Register (vol. 43, no. 132, pp. 29617-29618), "Appendix A - Guidance for Development of Lake Classification Information," more specific guidelines are provided. Included is the requirement to describe the lake watershed in terms of area, land use (list each major land-use classification as a percentage of the whole), and the general topography including major soil types. In addition, the major point and nonpoint sources of pollution are to be identified.

The Congressional mandates place a heavy burden on the States. Currently only 10 of the 50 States have complied. The application of space technology may be of great assistance to the States in meeting the mandates.

Coupled with recent technological advancements, additional research will yield results which may be of great value in:

(1) Developing lake classifications

(2) Developing priority listings for lake restoration purposes

(3) Providing estimates of specific water quality parameters (e.g., Secchi depth, chlorophyll a)

(4) Discriminating between organic and inorganic turbidity

(5) Monitoring change in land use in lake watersheds and its impact on lake water quality

(6) Aid in the development of management strategies to maximize the effectiveness of programs designed to minimize the impact of human activities on the environment

(7) Generating maps which depict the spatial aspects of water quality parameter magnitudes, vegetation, etc. Such maps would be of value in the selection of sampling sites and monitoring changes in water quality.

There are numerous approaches to the problem of lake classification. The number and kinds of variables selected for use in classification schemes vary greatly; the analytical techniques used to measure water quality parameters vary; the temporal and spatial sampling density can range greatly. Trophic indicators that effectively classify water bodies in one region of the U.S. may be less efficient in another region. The use of space age technology may permit the investigation of the regionality aspects of lakes through the acquisition of a unique data base.

A refined approach is needed which capitalizes on water quality data collected through contact sensing of a selected group of water bodies and watersheds and is then extended to a larger population. This will require that additional research be conducted in the following areas:

(1) Determination of the minimum number of contact-sensed water quality parameters which accurately characterize water quality

(2) Research into the development of a classification approach which has broad universal appeal and application over a wide geographic area

(3) A broad research program which further investigates the relationships between lake water color as seen by remote sensing devices and water quality parameters as measured by contact sensing

(4) The optimum spectral bands (their placement, width), sampling frequency, and spatial resolution required to accurately measure lake water quality and lake dynamics using multispectral radiance data

NASA technology has been and is currently being applied (on a small scale) to the problem of lake classification (refs. 7 to 10). Little work is being done to relate watershed characteristics to lacustrine water quality; the focus is directed toward stream water quality-watershed characteristic relationships (ref. 9). Current efforts employing satellite-acquired data are hampered by the spatial and spectral resolution of the sensor, and a variety of effects (e.g., atmospheric, instrument noise). The need exists to refine the current approach and extend it over larger and different geographic areas. Work is presently underway on multispectral analysis of high-altitude NASA photography to quantify land-use patterns and the effects on water quality of parts of Lake Michigan (ref. 11).

By their very nature, lakes are "dynamic." In addition, they are subject to change due to human activities. Therefore, it is necessary to update a lake classification on a periodic basis. The project evolves into one of long-term monitoring.

NASA's contributions can include the development and application of techniques to reduce peripheral effects (e.g., atmospheric, solar angle, instrument noise) found in remotely acquired data. In addition, it can contribute through the continuity of currently acquired multispectral scanner data.

2. Wetland Mapping and Role Assessment. Wetlands are recognized as a valuable resource. Yet there is constant pressure from a variety of special interest groups to drain and/or fill them. The problem arises of determining the role wetlands play in the natural environment. Initial questions which require answers include:

(1) Where are the wetlands?

(2) How large is each?

(3) What is species composition in each?

(4) Do they serve as nutrient traps or sources? How effective, if at all, are they in this regard?

(5) What would be the environmental consequences resulting from their elimination?

There now exist a number of legislative mandates which require the establishment of wetlands inventories within the conterminous U.S. and Alaska. The understanding of the nature, extent, and location of wetlands is incomplete. The basic problem is one of assessing in detail the role of wetlands as a component of the natural environment.

The wetlands' roles as important natural resource areas are highly varied. They serve as breeding and habitat areas for the commercial fish and shellfish industry. Wetlands act as natural aquifer recharge regions. They are known to serve as flood protection zones and even as tertiary facilities for sewage treatment.

As a result of the incomplete knowledge and information on the location, extent, and types of wetlands systems (marine, estuarine, riverine, lacustrine and palustrine), it is not possible to quantitatively consider their roles in aquifer recharge, or the value of these areas as wildlife breeding grounds or as wildlife habitats. The relative stability of these resource areas is unknown. It is known that wetlands act as inorganic turbidity traps and as a source for vegetative detritus which serve as food for fish and shellfish. It is important to understand how this delicate state of equilibrium is maintained or altered as a function of man's activity.

There is a generally recognized ecosystem relationship between, for example, lacustrine wetlands, lakes, and surrounding lake drainage. Wetlands have the ability to retain inorganic sediment runoff, including phosphorus, and thus reduce the influx of this biostimulant into the lake. This process may result in control of chlorophyll and algae production. These relationships are not well understood nor are they readily predictable.

Some research is being conducted by NASA, but more concentrated and intensive efforts are needed to identify and research areas where multispectral data can be used effectively to locate, identify, map, and quantify the various wetlands types.

Landsat multispectral data at the current 80-meter resolution is marginal for high accuracy wetlands mapping and characterization. Anticipated and future Earth resources missions, such as the proposed Landsat D with 30-meter resolution, should be adequate. In addition, the spectral selection of Landsat D will be superior to existing scanners. The ability to discriminate the various species most frequently seen in wetlands areas will be greatly improved.

An experiment using Landsat D capability mounted in a high-altitude aircraft would prove very useful in determining overall capability. A test area, previously mapped via traditional techniques, should be selected and compared and evaluated using multispectral methods. Wetlands must be mapped during the various growing seasons to determine temporal differences.

Water quality parameters for stream input should be compared to those determined for output. These data must be analyzed to assess the wetlands' ability to absorb and retain nutrients and other materials which would normally be transported to a lake. It is anticipated that the detailed research would take about 3 years to accomplish. At that point, the program would involve long-term monitoring.

3. Attached and Floating Macrophytes. The increased nutrients that have been added to our nation's waters through land runoff and industrial and municipal discharges have led, in many cases, to greatly increased growth of attached macrophytes along our lake shores and, in small water bodies, to masses of floating plants. These plants cause many water-use problems, such as clogging water intakes, interfering with boating and fishing, rendering beaches unusable, etc. This problem is one aspect of the more general problem of cultural eutrophication, which is discussed subsequently in section II.B.5; however, since the effects and monitoring requirements of this aspect are quite distinct from the more general problem, they are discussed separately here.

We have a fairly good general understanding of the causes of the problem growths of macrophytes. Improved methods of evaluating the extent of the problem and of monitoring the effects of remedial actions are needed, however, as is a much better understanding of the quantitative relation between macrophyte growth and such factors as light, nutrients, water movements, etc.

Elimination of problem growths of macrophytes is part of our national goal of cleaning up our waters. Elimination of the growths will improve the value of our waters for boating, fishing, swimming, drinking, etc.

Problem growths of macrophytes have had an especially severe impact along the Great Lakes. There the alga, Cladophora, has become very abundant in many areas and is probably the aspect of eutrophication that has most affected the recreational use of the Great Lakes and that has most led to public outcry. Similar problems, although often caused by different plants, are common in many other lakes and reservoirs, especially in the southern states.

Laboratory work is needed to determine the quantitative relations of macrophyte growth to its control factors. The resulting ideas need to be verified by field experiments and the relations synthesized in the form of a mathematical model. Further, the extent of the problem in our nation's waters needs to be evaluated and followed through time, especially in areas where control measures are implemented.

The maximum extent of macrophyte growth needs to be determined once a year for each ecosystem where there is a serious problem so the status of these nuisances can be determined and followed. Also, it would be very useful to follow seasonal changes in extent and biomass in selected areas in an attempt to provide information that can be related to data on control factors such as light, temperature, nutrients, etc. At present, the extent of problem macrophyte growths is evaluated primarily from the ground and is time-consuming and expensive. A remote sensing method to make these assessments in a less expensive and more synoptic manner is strongly needed. Since the need for assessment of problem macrophyte growths will unfortunately continue for a number of years, this is a long-term problem.

There is a great potential for NASA's contribution to the solution of this problem by developing means to monitor, with remote sensing, the extent and biomass of problem macrophyte growths along the shores of the Great Lakes and in a number of other areas. Some work has already been conducted indicating the promise in this area but also clearly showing the need for further development of the techniques (ref. 12).

4. Synoptic Measurement of Water Movements. A fundamental component of the qualitative and quantitative understanding of the biological processes in large water bodies is the transport of dissolved and particulate material. The need for estimates of these fluxes is basic to any investigation of the problems discussed herein. Therefore, methods of directly measuring water motions and fluxes of material at the relevant time and space scales are of great practical utility.

Currently available methods of measuring bulk transport are based on direct measurements of velocities and concentrations at discrete points in space (Eulerian measurements) or tracking drogues (Lagrangian measurements). Both of these methods have their limitations. Current meter measurements are usually of limited spatial coverage which severely restricts the ability to interpolate and extrapolate a comprehensive transport pattern. Tracking drogues provide integrated measurements of velocity; however, they are usually few in number and the period of tracking is less than desired.

The ability to make improved measurements of synoptic circulation would greatly add to the reliability of mathematical models that combine transport and kinetic processes. The transport structure of large lakes and coastal waters is an integral part of these calculations, the results of which can be used as an aid to decision making and rational water quality management. If the calculations are sufficiently accurate, surface elevation measurements can be made; these data can also be useful for the calibration of numerical circulation models.

Currently available capability can be used to make synoptic measurements of surface temperature. This is directly useful as water temperature directly affects biological and chemical reaction rates. Coupled with numerical models of water circulation, temperature is an important calibration variable. The sensing of wave heights is a fundamental component of sediment scour and resuspension calculations and is directly usable.

Synoptic tracking of many drogues can provide more comprehensive velocity data with which to calibrate the numerical circulation models. Hourly position information for the duration of the experiment would be required. Secondary information from remote sensing can provide indirect evidence for velocity field estimation. The distributions of river plumes provide a natural tracer. In the lower Great Lakes, the precipitation of calcium carbonate provides another tracer as well as being an important phenoménon that influences the growth of phytoplankton and possibly the phosphorus balance.

Specific requirements for Great Lakes circulation studies are for synoptic lake-wide circulation estimates at, perhaps, a weekly time scale. At this frequency, the dynamic time variable models could be compared to observations with sufficient frequency that their validity would be tested. Such measurements would initially span the ice-free season. These surveys could be coordinated with the planned intensive lake-wide surveys and would provide important supportive information. Of great importance would be the concurrent measurement of the transport field and variables of biological interest. Synoptic, concurrent measurement of water motion, chlorophyll a, light extinction coefficient, and suspended solids concentration would provide extensive data with which to formulate, calibrate, and verify mathematical models of phytoplankton dynamics and primary production. Such data, which are not currently available, could contribute to the development of more comprehensive and detailed mathematical models which relate the biological, chemical, and physical processes that determine phytoplankton production and seasonal distribution.

5. <u>Monitoring of Phytoplankton Standing Crop and Productivity</u>. As man's population and culture have developed, larger and larger amounts of plant nutrients have been introduced into freshwater and estuarine environments. In many cases these nutrients have caused great increases in plant growth, and these have led to overenrichment of specific water bodies with attendant water quality deterioration in the form of oxygen depletion, undesirable species shifts, masses of decaying algae on bathing beaches, etc. This problem, which is generally referred to as cultural eutrophication, has become of great significance in many areas and most importantly in the Great Lakes (ref. 13). There is a great need to follow the status of cultural eutrophication around the coasts and in the lakes of the United States so that the magnitude of this problem can be assessed over time and the causes of this problem in areas of greatest impact can be understood.

At present, we have a fairly good general understanding of the relation between phytoplankton growth and nutrient concentration. However, our understanding of how changes in absolute and relative concentrations of nutrients affect the number and relative importance of the various types of phytoplankton is much less adequate. Our knowledge of the status of eutrophication and its causes in specific areas is very patchy and especially poor for many of our estuaries and coastal bays.

Cultural eutrophication has contributed to and, in many cases, has been the major cause of the environmental deterioration of lakes and coastal areas of the United States. For example, the well-known deterioration of Lake Erie was largely caused by nutrient overenrichment and its subsequent impact on the ecosystem. We have adopted a national goal to clear up our water and control cultural eutrophication. Eutrophication has been probably the greatest cause of freshwater environment degradation and a major cause in estuarine areas. Its abatement is of high national concern and would improve the value of these areas in many ways; e.g., decreased costs for treatment of drinking water, improved sport and commercial fishing, increased opportunities for high quality recreation, and, more generally, increased aesthetic appreciation of our shore areas by all who live near or visit these areas.

The problem of cultural eutrophication takes somewhat different forms in different areas. As the different areas have quite different concentrations of the important nutrients, different nutrients are likely to cause enrichment problems. Also, composition and functional relations vary greatly among ecosystems and so the biological consequences of overenrichment can be site specific.

Chlorophyll is generally agreed to be the best integrated indicator of the status of eutrophication. Thus, its measurement in a given environment over a series of years should give a picture of the trend in eutrophication. Measurements for a number of years are required so that natural variability can be evaluated and separated from trends caused by man's activities. Also, fluctuations in temporal and spatial distribution of chlorophyll should be studied as these can provide valuable clues as to the sources of nutrient inputs and the relation between chlorophyll concentrations and nutrient amounts.

Chlorophyll measurements on approximately a weekly basis over the season of active algal growth are required to assess the status of eutrophication. Spatial scales of 1 km should be adequate in most cases although finer scales will be required at times for understanding of cause and effect relations.

Presently, chlorophyll measurements are made from water samples collected by ship. This procedure is very expensive and never gives as completely synoptic information as desired. A method for collecting truly synoptic chlorophyll values over many different water bodies is needed. Inasmuch as the need to assess the trends and status of eutrophication will continue as long as there are increasing nutrient additions due to man's increasing populations and activities, this is a long-term problem.

6. Identification and Quantification of Major Functional Groups of Phytoplankton. Eutrophication is a problem of major concern in freshwater lakes. A principal manifestation of the eutrophication process is the excessive production of phytoplankton biomass. Chlorophyll concentration is the most widely used indicator of phytoplankton biomass and, hence, of lake trophic status.

A serious drawback to the use of chlorophyll concentration is that chlorophyll is a lumped parameter and contains no information on individual functional groups of phytoplankton. The typical succession pattern of species in eutrophic, freshwater lakes is from diatoms to greens to blue-greens. Dinoflagellates usually occur sometime between the end of diatom peak and the beginning of the blue-green peak.

From a scientific standpoint, there are important differences among the above phytoplankton groups. All the groups have an absolute requirement for phosphorus; however, diatoms are the only group which have an absolute requirement for silicon. Certain species of blue-green algae have the capability for fixing atmospheric nitrogen when dissolved available nitrogen becomes depleted in the water column. Diatoms, greens, and dinoflagellates are desirable food sources and are subject to zooplankton grazing. Blue-greens are not grazed to any significant extent.

Distinctions among different phytoplankton groups are also important from a management standpoint. Blue-greens are usually considered to be "nuisance" species because of their tendency to form thick mats and surface scums. Blue-greens have been implicated as causative factors in taste and odor problems at water treatment plants. Since blue-greens are not assimilated into the food chain, they tend to be very persistent and they contribute a disproportionate share to the depletion of dissolved oxygen upon death and decomposition. Some species of diatoms consist of very large cells. Large blooms of such species have been known to cause serious filter clogging problems and shortened filter runs in water treatment plants.

Beyond the determination of chlorophyll concentrations, a principal characteristic feature of a eutrophic body of water is the seasonal succession from more desirable phytoplankton species to less desirable species. Species successional patterns have been well studied on a relatively small number of lakes.

In a typical study, identification and enumeration are conducted at the species level. In the more comprehensive studies, cell volumes are measured and biomass concentrations are computed. These data are usually related to simultaneous measurements of appropriate chemical parameters. In small lakes of several hectares in area, measurements are usually conducted at a single station at time intervals of 1 to 2 weeks. In large lakes of several thousand square kilometers in area, such as the Great Lakes, measurements are usually conducted on a spatial scale of 10 to 20 kilometers and a time scale of 1 to 2 months.

Major gaps in understanding are related to the lack of sufficient resolution in space and time and to the lack of sufficient data for all but a relatively few bodies of water. Significant changes in phytoplankton species composition can occur over time scales as short as 1 week or less. Different water masses in the same body of water can have significantly different species compositions at the same time. Such spatial "patchiness" can occur over scales of several tens of kilometers. There is a need for synoptic data on a time scale of at least 1 week and a spatial scale of approximately 100 meters. A major constraint on obtaining this type of information is the enormous cost and time involved in the processing of each sample by human means. Only a highly trained individual can identify, enumerate, and measure the hundred or more species that could potentially occur in each sample.

The problem of eutrophication has been addressed in the Legislative mandates of Public Law 92-500 to implement Best Practicable Treatment (BPT) and Best Available Treatment (BAT) methods for controlling phosphorus discharges from municipal wastewater treatment plants. The renegotiated 1977 Water Quality Agreement between the United States and Canada contains specific phosphorus loading objectives for each of the major basins in the Great Lakes.

Economic as well as aesthetic benefits will be realized by reducing eutrophication as well as reducing the overproduction of undesirable phytoplankton species. Examples are enhanced property values, use of waters for bathing and boating, and reduction of filter clogging and taste and odor problems in water supplies.

Specifically, the availability of high resolution synoptic data for major phytoplankton groups will be most useful in the calibration and verification of mathematical simulation models. Such models are becoming increasingly important in comparing the effects of alternative wastewater management strategies. Models have been developed which can describe the dynamics of different functional groups of phytoplankton. These tools can be used to directly address the separate problems caused by overproduction of blue-green algae.

A coordinated program of laboratory experiments, field studies, statistical analyses, and mathematical modeling will be required. Laboratory studies will be necessary to determine remote sensing signatures for the phytoplankton. Field studies are needed for ground truth. Statistical and modeling studies are needed to provide a conceptual framework for data interpretation and to ensure the internal consistency of the data.

Synoptic data on major functional groups of phytoplankton are required on a time scale of 1 week or less and a spatial scale of at least 100 meters. Cell volume measurements need to be made at the species level and then integrated to the desired level of resolution. This will need to be done for both laboratory-scale experiments and for ground-truth acquisition. The phytoplankton resolution should be at least to the level of the major groups, ideally to the level of the dominant species.

The data should be parameterized in terms of biomass concentrations and associated statistics to quantify the variability of the data. Color images as well as tabulated concentrations should be produced. Processed data should be available on computer compatible tapes.

Currently, all data on species or group composition must be acquired by human means. Samples are taken at discrete points, and time-consuming identification, enumeration, and cell volume measurements must be conducted. Technology is needed which could greatly reduce the labor-intensive aspects of present methods.

A long-term study is required because one of the major uses of the results would be to quantify the long-term response of a system to changes in nutrient loadings. Such long-term monitoring, in a synoptic sense, is strictly prohibited by the enormous costs involved.

7. Assessment of Fish Stocks in the Great Lakes. The establishment of significant populations of salmonoids and lake trout in the Great Lakes has been a major accomplishment of state natural resource management departments. During the last 100 years there have been tremendous changes in standing stocks of many species due to a variety of reasons, including eutrophication and the introduction of foreign species. At the present time, there is also considerable concern regarding the role of fish in transferring toxic pollutants to man.

Because of the changes in water quality and introduction of foreign species, there are tremendous variations in the populations of different species (some of which, such as the salmonoids, are controlled by fish management practices). The major factors that have affected the standing population in the four lower lakes are the introduction of the sea-lamprey and alewife, marine species which entered the lakes as a result of the completion of the Welland Canal, and for Lake Erie in particular, cultural eutrophication. As a result, there has been a major shift in the species of fish found in all the lakes. In the upper lakes, a major factor was the gradual loss of the top-predator species, lake trout, due to attack by the sea-lamprey and overexploitation by the commercial fishery. As the commercial fishermen shifted their efforts to the coregonids, these species also suffered sharp declines. As a result of no predation and an unpopulated niche, the alewife successfully colonized and their population exploded.

Since the middle sixties, several different species of Pacific and Atlantic salmon have been introduced into the Great Lakes and there is now a thriving and profitable sport-fishing activity in several of the lakes. The establishment of this fishery was predicated on the ready availability of sufficient forage fish to support the introduced populations of salmonoids.

In order to protect this fishery and perhaps to reestablish the coregonids, there is a need to predict the magnitude of the populations of forage fishes so that the introduction of salmonoids does not exceed the carrying capacity of each lake. At present, the methods of estimating fish populations are not that accurate. They are largely based on fish counts from standard trawls and sophisticated parametric statistics. These predictions should include measures of the standing crop of forage fishes, recruitment (identification of spawning grounds and larval distribution), and losses (natural, predatory, and impingement or entrainment at water intakes for cooling systems or water supplies).

The achievement of reasonable predator-prey relationships in the fisheries of the Great Lakes is important both for the long-term water quality of the lakes and for the economic stability of many communities around the shores of the lakes. It is now recognized that the sport-fishing industry has had a significant impact, which includes not only the value of fish themselves but also the development of a significant tourist industry: boatbuilding, sales and chartering, fishing tackle industries, etc.

As mentioned above, the estimation of the standing crop of forage fishes in the Great Lakes has traditionally been made by fish counts from standard trawls over specified areas of each lake at specified times of the year. Recent work by Magnuson and Clay (ref. 14) has demonstrated the feasibility of whole Great Lakes assessment of pelagic fishes by advanced acoustic systems. The results are obtained both in terms of number of fish and biomass. Their work has already been applied to the alewife in Lake Michigan and is now being used to assess the smelt population in western Lake Superior and the salmonoid populations in Lake Michigan. Though the technique requires significant ship time, it is far more efficient than, as well as superior in sampling coverage to, trawling or other capture techniques.

The assessment of fish populations is a continuing and major need for effective management of natural resources of the Great Lakes. The techniques would be applicable to all lakes and coastal fisheries.

C. Marine Systems

1. Sources and Sinks of Biochemically Important Factors. The coastal marine ecology is influenced by diverse fluxes of biochemically important substances. Nutrients essential to plant growth enter the coastal region from offshore, and from rivers and diffuse terrestrial runoff. Water pollutants, whether excess nutrients or toxic chemicals, also enter from the terrestrial environment. Entrained sediments and dissolved compounds, also typically carried by freshwater runoff, tend to increase water turbidity and this limits the depth of the euphotic zone. River outflow also has a significant impact on local dynamics, e.g., by creating ocean fronts, and, in the case of major rivers, may control the salinity of vast stretches of the continental shelf. Because these varied substances control the health and quality of our coastal ecosystem, it is vital that we understand their role. Complete understanding of this problem requires determination of each substance's sources, as well as its rate of input, transport, diffusion, residence time, and ultimate fate.

The sources of critical nutrients in primary production in the coastal ecosystem are oceanic and terrestrial, the latter mainly taking the form of freshwater flow. The rate of removal of the nutrients is primarily controlled by the abundance of phytoplankton and their productivity, export through diffusion and circulation, and sedimentation. Resuspension and redissolving of sediment through tidal or wind-induced mixing and microbiological processes can be an important facet of nutrient redistribution and cycling. Anthropogenic substances enter the coastal waters through freshwater discharge and intentional disposal. They include heavy metals, halogenated hydrocarbons, petroleum hydrocarbons, agricultural fertilizers and pesticides, and artificial radionuclides. They may have accelerating, inhibiting effects on primary production and impact significantly the entire marine food web.

Although we understand the general principles and mechanisms involved in sources and sinks of nonpoint-source pollutants, we do not have the information required to quantify the rate of input and total volume of these materials. Furthermore, we have only a conceptual understanding of physical transport by currents in coastal waters, and we do not have a quantitative understanding of the relative importance of advection and diffusion as compared to biological and chemical change processes.

The lack of an adequate synoptic data base over relatively large areas precludes both the quantitative description of the system and prediction of its essential characteristics. The scales of these phenomena, combined with the slow speed and sampling capabilities of research vessels, render traditional oceanographic sampling schemes inadequate to this task.

The primary research task needed to attack this problem is to obtain large-scale synoptic measurements of conservative and nonconservative properties of the coastal oceans. The results of this effort should first yield a quantitative description of water mass movement and advective effects. In addition, measurements are needed to determine biochemical cycling mechanisms and rates. A partial list of specific problems to be attacked through such an observational program includes:

(1) Sources of water in different parts of the coastal zone

(2) Impact of estuaries on adjacent coastal zone biology, O_2, and chemistry

(3) Distribution of bottom sediment types and nutrient flux from sediments

(4) Where does N, which drives shelf productivity, come from? Is N the most important variable controlling productivity in the coastal zone?

(5) Identification of nutrient source locations and measurements of input rates

(6) Measurements of synoptic nutrient concentration fields: N, P, S, metals, and organic chelators

At the present time, many of the associated parameters must be measured from research vessels. To the extent permitted by state-of-the-art technology, remotely sensed parameters can, and should, be used to extrapolate and interpolate in situ point measurements to estimate spatial distributions which cannot be determined from ship sampling alone.

2. Synoptic Mapping of Nutrients. The major driving forces in primary production, and therefore eutrophication, are temperature and the concentration of the major nutrients, C, N, P, and Si. Measurements have shown that the rate of production decreases when any or all of the nutrients are depleted. Shipboard measurements also indicate that there is a tremendous spatial variability in these concentrations which can occur from a wide variety of causes. For example, in the Great Lakes where there is little tidal action, wind-driven water movements can lead to rapid depletion or renewal of nutrients with concentration change in productivity or species composition if any one nutrient is depleted.

In order to obtain better estimates of primary productivity and to more fully understand the patchiness observed between biomass and nutrient concentration, it is clear that more detailed synoptic measurements of the relevant parameters are necessary. Present capabilities produce intermittent quasi-synoptic data depending on the vagaries of ship scheduling. This severely limits our ability to assess present conditions and develop and calibrate more detailed numerical models.

Eutrophication is one of the major factors in defining water quality and a considerable effort is being expended to manage aquatic systems to attain or maintain water quality standards as defined by state and federal regulatory agencies.

Chemical species in surface water which exert critical control on primary production in the oceans' chlorophyll are:

Species	Average concentrations, mmoles
Water	5.5×10^4
Sulphate*	30
Carbonate	2
Silicate	0.2
Nitrate	6×10^{-3}
Alkalinity	6×10^{-4}
Phosphate	2×10^{-4}

*Value for open ocean: far less in many freshwater lakes.

The particulate and dissolved organic components in surface water also reflect not only the primary productivity therein but may be useful in locating fish stocks which are attracted to the materials; thus, a mapping of the organic levels in the surface layers can be of value to both the ecologist and the fishery biologist. The particulate and dissolved organic component distributions and concentrations in surface and near-surface waters would also be useful in determining organic loading from estuaries (including major metropolitan areas) to the coastal ocean.

Variations in productivity occur on time scales as short as a few hours and as long as a few months, with diurnal and monthly variations being very significant. If we are to understand the dynamics of natural water sufficiently to predict the effects of stress, measurements will have to be made of nutrients over time spans which allow us to determine the variance associated with all types of natural phenomena, such as water levels, microclimate, etc. Therefore, synoptic measurements covering large areas of major water bodies and the complete area of smaller lakes and watersheds are needed at frequent intervals. Present measurements are made sporadically depending on cruise plans of research vessels using automated chemical techniques. These can be flow-through or grab samples. Intensive data are available for small areas in many ecosystems either on a monthly schedule or sometimes more often when major experiments are being conducted. The techniques do not guarantee that major changes will be detected even at a particular location, and spatial relationships are, in general, completely lacking.

3. Plankton Abundance - Phytoplankton Patchiness. Major concerns in marine food chain studies include the determination of physical stresses on lower trophic levels, and determining the degree of coupling between various trophic levels. Examples of the former are factors controlling the abundance and distribution of phytoplankton, and the dynamics of patchiness of phytoplankton. Patchiness in zooplankton and ichthyoplankton are major factors in coupling primary and secondary production.

This area is probably the most heavily supported in biological oceanography, with several ecosystem approach studies in progress. Some points of relevance are that (1) the size spectra of the phytoplankton community affects the nature of the entire food web (number of steps in the chain), (2) certain persistent pollutants and eutrophic processes can determine phytoplankton size distributions, (3) natural communities show seasonal changes in size structure apparently related to degree of mixing and nutrient cycling, and (4) interaction of relatively small-scale 20-40 km (x,y) and 1-2 km (z) patches of phytoplankton and larval fish determine successful first year class.

Assessing the three-dimensional structure of the plankton community is still a major area of effort. Phytoplankton patches occur on the order of 10-20 km scales horizontally and within meters vertically to below pycnocline depths. Patches appear to be persistent features tied to topography in many instances, but identification of these areas is incomplete. Characterizing the community on a pigment basis (greens versus blue-greens in diatoms versus dinoflagellates) or a size basis (nanoplankton versus net plankton) is critical to understanding the trophic transfer processes.

4. Global Primary Productivity. Primary producers are at the base of the food web and shifts in distribution, in magnitude, in dominant species, or in size classes can have major impacts on higher trophic levels. Additionally,

because the major primary producers are of small size and have relatively short generation times, they respond relatively quickly to environmental change and thus could play a role as a so-called "early warning system."

The measurement and determination of primary productivity is reasonably well determined and accepted. Measurements exist for many areas of the world to the extent crude estimates of major large areas can be made. Shifts in global primary productivity are manifestations of global teleconnections.

In spite of numerous investigations and considerable effort on the part of many countries, global levels and distributions of primary production are too poorly known to relate to higher trophic levels over large regional areas and short time periods. The major problem has been the inability via sea surface measurements to cover large geographical areas with dense sampling frequently enough to adequately define magnitudes of primary productivity on a seasonal basis.

Determination and continuous monitoring of global primary productivity related to climatological and physical oceanographic shifts would increase our understanding, predictability, and management of the global ecosystem. However, global levels of primary production could be determined indirectly but accurately via tight temporal and spatial mapping of chlorophyll concentrations determined remotely along with relatively few concurrent shipboard measurements of primary productivity for calibration.

5. <u>Quantitative Linkage Between Primary Producers and Upper Trophic Levels</u>. The problem of sampling adult fish stocks and juvenile or larval assessments is difficult due to the patchy nature of their distribution and the mobile nature of the stocks. Apparent distribution and abundance estimates may really be due to sampling artifacts. These artifacts reappear in the annual quotas that are part of the legislatively mandated fishery management plans; hence, they strongly affect management of coastal fisheries.

Quotas are generally derived from yield models that assume a steady-state environment. Further, the recruitment input to these models is often from shipboard station data (trawl or plankton net). In some cases, notably the menhaden or anchovy, it has been shown that physical processes such as surface Ekman transport or primary biologic processes such as dinoflagellate/diatom bloom ratios contribute substantially to the success or failure of recruitment. Ship-collected data are discontinuous and sampling may miss areas of abundance - or may fortuitously cover sample patches of high abundance. These data on adult stock abundance and recruitment (larval abundance) are so variable that their use as input in yield models often results in serious errors in yield estimates and hence quotas. Public Law 95-264 (Fisheries Conservation and Management Act of 1976) is a Congressionally mandated statute requiring the development and operation of management plans for each fished stock. Realistic stock assessments of recruitment and abundance are difficult to secure yet are required so that the annual mandated quotas can be generated.

Remotely sensed data on the location, size, and duration of eddies, upwelling, surface windfields, or planktonic blooms used in conjunction with shipboard stock assessments will reduce the patchiness of the data, provide criteria for more efficient surface sampling, and will allow repeated synoptic measurements of these features. The most significant U.S. coastal fisheries lie within 300 km of the coast line over the continental shelf. Remotely sensed assessment data from the Bering Sea, Gulf of Mexico, Atlantic Bight, and Georges Bank would provide the most significant input.

Work is needed in (a) the development of species-by-species conceptual models of how the environment perturbs the recruitment process, and (b) the evaluation of which causal environmental factors are best sampled from remote platforms.

One experiment currently being planned is the Large Area Marine Productivity Experiments (LAMPEX) cooperative effort between NMFS (NOAA's National Marine Fisheries Service) and NASA which will encompass a quasi-synoptic coastal waters chlorophyll assessment from NASA aircraft and NMFS vessels. Specific directions that such researchers might take include the following:

(1) Measurement of areal extent of phytoplankton concentrations at surface and at depth

(2) Quantitative estimates of concentrations of chlorophyll

(3) Delineation and measurement of flow of Ekman transport daily over spawning grounds

(4) Measurement of sea surface temperatures, thermocline topography, and bottom (shelf) temperatures daily and weekly

(5) Measurement of salinity profiles and pycnocline topography

Current sea surface temperature and salinity estimates are within acceptable limits; however, subsurface measurements are needed along with Ekman transport volumes and quantitative primary productivity measurements. Some degree of taxa recognition might be provided from remotely sensed platforms (e.g., dinoflagellates from diatoms, copepods from euphausids).

The period of study is expected to be long-term and, after initial experiments, monitoring of stock recruitment and abundance will continue until patterns are established.

6. Catastrophic Events. Marine and estuarine biosystems are subject to unusual perturbations or catastrophic events, as follows: (1) Red tide blooms of dinoflagellates (toxic or nontoxic) leading to paralytic shellfish poisoning or environmental anoxia, with resultant kill of marine invertebrates and fish; (2) unusual temperature stress, as in the extremely cold winter of 1977, and the discontinuation of upwelling along the coast of Peru and California which results in major disruptions at all trophic levels; (3) unusually high freshwater runoff resulting in greatly lowered salinities and resultant morbidity or death of some populations (notably shellfish); (4) the accidental or deliberate discharge of petrochemicals, toxic materials, and sewage into the aquatic environment; and (5) thermal stress through power plant shutdown. Can such events be identified and their extents and durations be determined by remote

sensing? Additionally, can the coastal waters of the United States be monitored for significant deviations in temperature, salinity, chlorophyll, and certain contaminants (organic and inorganic) to predict or provide an early warning indicator of a catastrophic event?

7. Temporal and Regional Variability of Surface Features. Knowledge of the location of features which exist as relatively small scales (under 10 to 100 km) is of critical importance for designing and conducting sampling programs. Many of the currently important research problems in physical, chemical, and biological oceanography occur in particular locations which are known about in general but which cannot be adequately sampled due to a misfit between the spatial and temporal scales of the problems and ship capabilities. Ocean fronts will be considered here as an example of the problem.

Fronts are sites of intense physical activity which lead to enhanced biological dynamics. Coastal fronts may persist for periods of months to years; however, physical processes leading to enhanced biological processes may operate discontinuously with time (ref. 15). We need to know the location and structure of features associated with fronts as well as the time variation of these features. We need to know the forcing variables which control the highly dynamic features associated with fronts. Fronts may be a major source of enhancement of food web dynamics leading to fish production in coastal waters (ref. 2). Fronts are also sites where particulate material and oil can become concentrated and they have been implicated in generation of red tides.

Accurate location of features of interest on the ocean surface can be achieved with existing remote technology. Improvements in technology will provide increased capability for solving some of the problems of frontal dynamics. This will benefit the scientific community as well as management and regulatory agencies at the federal, state, and local level.

Strongly developed physical features are frequently sites of strong change in chemical and biological fields within aquatic systems. Examples of this are upwelling fronts, river plume fronts, and shelf break fronts. The location and characterization of features for surface sampling purposes is therefore of primary importance for the solution of problems in all aquatic systems.

There are currently several programs funded to investigate frontal processes which might serve as tie-ins for NASA technology. NMFS, in particular, would be a prime user in relation to assessing fishery resources. The type of work required to develop capabilities for front location would be a cross-check of sensor responses with surface truth.

Temperature, salinity, color, surface reflectance, surface roughness, or some combination of these will be required to locate features of interest. Spatial resolution scales are from 100 m to 1 km, at the minimum, to resolve structure in fronts. Resolution, the order of 10 km, could serve to locate fronts but could not position ships within, for example, chlorophyll maxima in fronts. Data product format should be maps of variables available for delivery from 3 hours to 1 day after observations are made. The time scale requirement depends on whether the maps would be used to locate ships for research objective satisfaction or for fishing effort assessment. Frequency of remote sampling will be defined by temporal variations in dynamics of forcing variables.

Aircraft platforms appear to be more promising in terms of sensor capability, data resolution, and cost-effective remote sampling in the coastal zone than satellite platforms planned for the near future. The Coastal Zone Color Scanner (CZCS) appears limited in sensor resolution, which may be too coarse for location of biological features such as fronts, limited in lack of salinity sensing capability, and limited by insufficient sampling frequency. Geostationary satellites with adequate resolution in visible, thermal, and microwave channels with direct telemetry links to data processing centers so that data can be made available to ships at sea via satellite linkage would provide a powerful capability for investigating bioprocesses and factors which control the processes.

III. GAS AND AEROSOL FLUXES

Atmospheric chemical processes are intimately linked to hydrospheric process through the transfer of matter via aerosols and gases. These transfer processes (termed "fluxes" henceforth) are defined as the rate of transfer of mass per unit area per unit time. The global extent and patchiness of fluxes for a suite of geochemically important compounds represents a major problem area potentially amenable to remote sensing technology.

In the following sections, several compounds or groups of compounds for which aerosol and gas fluxes between hydrosphere and atmosphere are known to be important are discussed. A statement of the problem, brief summary of our present understanding, and suggestions for needed research are presented for each group.

A. Sulfur Cycle

A major entry in current global sulfur budgets is an unidentified flux from the Earth's surface to the atmosphere. The dominant site or sites of this flux as well as the chemical species involved are presently not known (refs. 16 to 19.)

Current global sulfur budgets are in reasonable agreement and suggest that a flux of approximately 150 ± 75 megatons of sulfur from land and ocean to the atmosphere is required for a balanced cycle. It has been argued that H_2S is a major species involved in the transfer and further that coastal mudflats, salt marshes, and estuaries, together with freshwater swamps, irrigated farmlands, and some lakes and runs are likely sites for this transfer. This supposition is to some extent supported by studies of stable sulfur isotopes in localized environments. However, recent data document the presence in the troposphere of CS_2, $(CH_3)_2S$, and COS and thus raise the question of a wider range of release mechanisms and sites (refs. 18 to 21). Recent measurements also suggest that tropical and subtropical oceans may be a source of gaseous sulfur compounds (ref. 21).

Man is influencing the global sulfur cycle directly. Problems include the global cycle and acid rain pollution problem mentioned above, health problems associated with sulfate, the climatic effect of stratospheric aerosol layers, and the overtitration of biological hydrogen ion buffering via ammonia. We cannot describe the role of sulfur species in controlling the pH of rain until the sulfur cycle is better quantified.

There are several areas of needed research. A major gap is the lack of quantitative flux measurements. The behavior of the major S species discussed above in both the water column and atmsophere is poorly understood. Man's demonstrated impact on the global sulfur cycle (e.g., refs. 16 and 22) points to a need to locate the sites of fluxes to the atmosphere. When the sites and important species are identified, the impact of fluxes on a hemispheric to local scale can be more readily assessed. Measurements of the fluxes of key chemical species across the range of environments from open ocean to coastal are needed.

B. Nitrogen Compounds

1. Statement of the Problem. The global nitrogen cycle begins with the fixation of atmospheric nitrogen. As an essential nutrient, fixed nitrogen is assimilated by organisms, discharged through their subsequent decay or as waste, further recycled through oxidation-reduction reactions, and returned to the atmosphere following denitrification (refs. 23 to 25). The rates of several of these processes are poorly known on a global scale. Furthermore, present data suggest that anthropogenic influences may be significant (ref. 24). A quantitative evaluation of the various components of the N cycle is important both for understanding the global N cycle and for assessing the impact of projected increases in usage of fixed nitrogen.

About 200 million tons of N are fixed annually by legumes, blue-green algae and lightning (ref. 24). Global fixation rates are reasonably well-known (refs. 23 and 24) with the exception of oceanic environments. For comparison, man's N fertilizer plants produced about 40 million tons in 1974 (ref. 24) and combustion processes released another 200 million tons. Man's estimated needs for fertilizer N in the year 2000 will be at least 150 million tons (ref. 24). Man's production of fixed N is having an impact on soils and waters where N is often the limiting essential nutrient (ref. 6). Nitrogen cycling in these environments will eventually modify fluxes between the hydrosphere and atmosphere. Alterations in atmospheric gas phase chemistry may result. For example, fixed nitrogen compounds may catalyze the destruction of ozone (ref. 24). Exactly how much control compounds such as NO_x exert over O_3 concentration must be better known to understand these processes.

2. Present Understanding. Nitrogen compounds are extremely important in the environment. In soils and waters, N is often the limiting essential nutrient. In the atmosphere, active N compounds (NO, NO_2, HNO_3) exert control over tropospheric gas-phase chemistry and NH_3 and HNO_3 in precipitation can control the pH. Nitrous oxide (N_2O) is the source of stratospheric NO_x (important in ozone-layer photochemistry). Increased N_2O will trap more outgoing planetary infrared energy.

Exactly how much control NO_x in the troposphere exerts over tropospheric O_3 and radical concentrations is unclear; ambient hydrocarbon concentrations, several kinetic rates, and the NO_x concentration themselves must be better known. Other gaps in present understanding include: Identities and concentration of organic N compounds in atmospheric particles; the extent of organic N enrichment of the marine surface microlayer; atmospheric (lightning) fixation rates; locations and strengths of NO and NH_3 sources to the atmosphere; and transfer rates between the global reservoirs of fixed N, e.g., runoff from the continents, annual N_2O sources, and nearly all aspects of the oceanic N cycle.

3. Needed Research. The following problems were identified from the above considerations:

(1) Measurement of denitrification rates in oceans

(2) Measurement of N_2O fluxes from oceans and inland waters to the atmosphere

(3) Monitoring of atmospheric N_2O to identify trends

(4) Measurements to elucidate N-cycle processes and rates in oceans, inland waters, and the atmosphere

(5) Isotopic studies of N compounds in waters and atmosphere to deduce sites, rates of fixation, denitrification, etc.

(6) Special attention to anoxic environments

(7) Regional and global measurements of HNO_3 and, if possible, other active N compounds (NO, NO_2) in the atmosphere

(8) Measurements of NO_3^- and NH_4^+ and organic N in precipitation in selected perturbed regions and over the open oceans

C. Methane

Recent measurements indicate that methane concentrations in the troposphere have risen by approximately 15 percent over the past decade. If these data are substantiated, significant effects on atmospheric chemical and radiative processes are forecast. It appears that anthropogenic production is one possible cause for the rise; however, the sites, mechanisms, and magnitudes of fluxes for terrestrial and marine methane reservoirs are unquantified.

The geochemical mechanisms for methane production and consumption in sedimentary environments are reasonably well documented (refs. 26 to 28). Transport mechanisms across the sediment-water and air-sea interfaces have likewise been elucidated (ref. 29). Preliminary flux estimates to the atmosphere based on limited data have been published (ref. 30).

We do not know the distribution of important flux sites and therefore cannot pinpoint a mechanism for the alleged atmospheric increase. Because atmospheric methane concentration variations have important consequences for global atmospheric processes, an understanding of the coupling between production rates and human activities is needed.

Technique development is needed for measurement of methane fluxes over reasonably broad (i.e., km) scales. While some methane sources seem well identified qualitatively (e.g., swamps, rice paddies, organic-rich sediments), quantitative measurements are needed to deduce their source strengths. Exploratory measurements are also required to identify other possible CH_4 sources.

D. Halogen Compounds

Interest in atmospheric halogen compounds is very high and research is required for several reasons. One is their role in atmospheric chemistry, specifically the high efficiency of Cl and Br in ozone destruction in the stratosphere. Another is the series of puzzles involving halogens in the marine aerosol.

Two broad problem areas are easily identified:

(1) What organohalogens are released from the oceans to the atmosphere and in what quantities? While it is known that CH_3Cl, CH_3Br, and CH_3I are so released, the processes, sites, and amounts of release are not clear. Also, many organohalogens have been identified in marine organisms (algae, seaweed, sponges) but no efforts are underway to detect them in the atmosphere.

(2) Halogens in the marine aerosol - there exists a sufficient body of data to characterize the Cl^-, Br^-, and I^- (or IO_3^-) contents of marine aerosols as functions of particle size and particle age. Key questions include the following: What processes account for the large enrichments of I on all particles and the deficit of Br (seen in all except fresh aerosols and in small aerosols near coasts where CH_2Br from automobile exhaust contributes Br)? Is gaseous inorganic chlorine in the troposphere (present largely as HCl) really due to Cl release from the marine aerosol as is generally believed? If so, what heterogeneous processes are responsible for the Cl release?

Other notable questions include: To what extent does tropospheric HCl control precipitation pH in coastal and continental zones? What are the atmospheric and hydrospheric pathways of high molecular weight, halogenated hydrocarbons (e.g., insecticides and dielectrics)?

The following studies are urgently needed: Natural sources of organohalogens especially the more inert ones, e.g., CH_3Cl, CH_3Br, CH_3I, and possibly larger molecules with more halogens must be identified; heterogeneous processes controlling gas-to-particle and particle-to-gas conversion; and the feasibility of employing easily detected chlorofluorocarbons as tracers of oceanic circulation.

E. Volatile Metals Transport to Oceans

Natural (biogenic and nonbiogenic) and anthropogenic mechanisms result in mobilization and subsequent transport of certain volatile metals including V, Hg, Se, Sb, As, Pb, and Cd to the oceans. A major transport vector to the open oceans results from the association of these metals with submicron particles; however, the flux is not well quantified.

Condensation processes lead to the association of the anthropogenically volatilized metals with submicron particles. Natural volatilization processes appear to produce the same effect for a select suite of elements. It can be stated that aeolian metal transport to the continental shelf rivals riverine transport; furthermore, aeolian transport is the major transport mechanism bringing metals from the continents to the open ocean. Recent studies demonstrate that significant solubilization of these metals occurs in seawater.

Aerosol residence times indicate that significant quantities of anthropogenic metals (e.g., Pb) are restricted to the northern hemisphere. An additional suite of low temperature volatile metals is observed to be enriched relative to predictions from crustal abundancies on a global scale.

Fluxes of these metals are poorly quantified on a global scale. Mechanisms of initial volatilization of these metals are poorly understood. Flux estimates are based on data collected at a limited number of surface stations. Synopticity is needed.

Flux information is needed in order to assess the impact of anthropogenic activities on the water quality of open ocean waters. Preliminary Pb measurements indicate that North Pacific surface waters are impacted by anthropogenic inputs.

We have emphasized open ocean transport processes; obviously coastal areas will be affected in a more localized fashion.

Needed research: "Ground-truth" aerosol composition information is currently being collected. A synoptic understanding of aerosol loading and trajectories in combination with deposition velocity is required for formulation of quantitative source/sink budgets.

F. Organics

The importance of the atmosphere serving as a significant route by which material is transferred to the ocean environment has become widely recognized as one result of studies on the origin of PCB's found in seawater. In addition, it is also known that organic material is ejected from the sea surface as a consequence of bubble bursting, and this material is retained in the atmosphere as a marine aerosol. The amount of material transported into the atmosphere by this process has been estimated to be comparable to that calculated to enter with marine precipitation. However, it is not possible at the present time to determine whether or not one is observing a cyclic phenomenon. Although there are several reasons why this problem persists, one of the more important is a lack of knowledge on the amount and content of material, particularly organics, in marine precipitation. Therefore, there is a need to gain an understanding of the detailed composition of marine dust, precipitation, and aerosols in order to resolve whether or not the presently measured atmospheric input is actually a source function or recycled material. As part of such a study, the chemical and photochemical processes in which organic material (including gases) participate should also be investigated.

The basic consideration here is whether the marine environment is a source or sink of organic material. At the present time, so little information is available that we cannot state whether a major marine environmental problem exists or not.

G. Flux Measurement Techniques

The term flux is used to connote a rate of transfer of mass per unit area per unit time. A knowledge of such transfer rates at air-water and sediment-water interfaces is essential if we are to understand the critical questions of water quality, marine chemistry, atmospheric chemistry (globally and regionally), and the geochemical cycles themselves. Yet we must realize that fluxes are not measured; concentrations are. The interpretation of the measured concentrations in terms of fluxes is a classic and vexing problem.

The available ideas and methods for estimating fluxes each suffer from drawbacks. None are generally applicable and most perturb the system under study to some extent. To be specific, closed chambers, open chambers, meteorological correlation methods, and measurements of concentration gradients or of concentrations on opposite sides of an interface (when accomplished by, say, a stagnant-film model) each have a domain of applicability and their own limitations. Further, we must face the general problem that there is patchiness in environmental sources and sinks, and transport by bubbles must be recognized. Therefore, whatever methods are used must be applied with enough spatial and temporal frequency to sample all the key environments accurately.

Research needs cover the following areas: Species-specific sensors to allow sampling of shorter duration and better time resolution; portable sensors to measure micrometeorological parameters to allow more application of meteorological correlation techniques; and guidance from biologists, sedimentologists, and meteorologists in selecting flux measurement sites and techniques.

IV. PARTICLE FLUXES TO THE AQUATIC ENVIRONMENT

A. Overview

Describing and predicting the transport and fate of particles in aquatic ecosystems are fundamental to the prudent use and protection of our nation's water supplies. Considerable research including field observations, laboratory experiments, and mathematical modeling has been and is being done in order to understand the various physical, chemical, and biological processes governing the disposition of particles.

Defining problems and research needs for the determination of particle fluxes of contaminants in aquatic ecosystems is considered herein. To do this, it is necessary to know not only the transport mechanisms, but also the chemical, biological, and even physical processes which transform the materials during their transport. Therefore, these processes directly affecting the particle fluxes of contaminants were also considered in our deliberations. It is evident from the output of the other three working groups that they also had to ultimately consider this problem of particulate flux.

Aquatic ecosystems can be conveniently divided into (1) drainage basins, (2) rivers and streams, (3) wetlands, (4) lakes, (5) estuaries, (6) coastal waters, and (7) open ocean. Many of the physical, chemical, and biological processes and hence the scientific issues and research problems are common to most or all of these aquatic systems. Nevertheless, the significant length and time scales are sufficiently different for each system that different processes may be dominant in each system. This means that the requirements for (1) data acquisition and analysis, and (2) conceptual and mathematical modeling are sufficiently distinct that it is reasonable to consider each system separately. Such a plan was followed, and the major research problems and needs for each aquatic system are discussed in the following pages.

A particularly important product of this meeting was the realization that many problems were common to several of the aquatic systems and could be investigated and analyzed in similar ways. The exchange of ideas between the limnologists and oceanographers was especially significant.

It should be emphasized that (1) the transport and fate of particulate contaminants are fundamental to problems of water quality and (2) it is these same transport processes that are most amenable to investigation by remote sensing, a most happy coincidence of problems and solutions. At the most basic level, remote sensing can be used to monitor quantities such as temperatures and concentrations of particulate matter, data that are necessary to assess the effects of man by comparison with natural conditions. This monitoring effort needs large amounts of data, i.e., wide coverage with sufficient detail in space and time to distinguish significant fluctuations. Surface ships and standard ground-based measurement systems generally cannot provide this information in sufficient detail for adequate characterization. Remote sensing is limited since it is restricted to measurements of near-surface parameters. However, the two procedures complement each other and together can give the data required.

Of equal importance to monitoring is our ability to understand the physical, chemical, and biological processes governing water quality. If we understand the basic processes and if we have sufficient data, we should then be able to predict, by means of conceptual and mathematical models, the effect of various man-induced changes on our aquatic systems and hence control these changes. This is our ultimate goal.

A considerable amount of work is currently being done to understand the physical processes of transport as well as the chemical and biological transformations occurring during transport. Conceptual and mathematical models are being developed to incorporate these processes into an overall predictive model. However, the modeling effort needs large amounts of data over large areas with all measurements preferably at one time, i.e., synoptic data. These data are necessary for initialization and verification of predictive models (as well as for a data base for monitoring and trend analysis). It is in this context that remote sensing can be valuable since no other procedure can furnish this type of synoptic and detailed data. This need is documented repeatedly in the following pages for each and every aquatic system.

B. Coupling of Drainage Basin Characteristics, Meteorological Events, and Human Activities With Lake Water Quality

Drainage basin characteristics (e.g., morphometry, soil types, land cover types), meteorological event characteristics (e.g., intensity and duration of precipitation), and human activities interact to determine water quality. Lakes of varying water quality are found in drainage basins essentially free of human impact as well as those heavily used by humans. They are affected to some degree through the influx of materials from both point and nonpoint sources. It is essential that a better understanding of the interaction between water quality and drainage basin characteristics, meteorological events, and human activities be attained so that actions can be considered and, if technologically and economically feasible, implemented to maintain or improve lake water quality. Several broad questions need to be answered.

(1) What are the relationships between drainage basin characteristics, meteorological events, and water quality in watersheds undisturbed by human activities?

(2) What are the relationships between drainage basin characteristics, meteorological events, and water quality in watersheds disturbed by human activities?

(3) Under what circumstances can the management of human activities result in the maintenance or improvement of water quality?

(4) In drainage basins subjected to human activities, how do the nonpoint source inputs to the receiving waters compare with inputs from point sources?

Congressional mandates exist (e.g., The Clean Water Act, Public Law 92-500) which direct that programs be developed and implemented to improve the quality of the nation's water. In response, for example, a sewage plant construction program costing many hundreds of millions of dollars has been implemented. In addition, the States must develop a process to identify, if appropriate, agriculturally and silviculturally related nonpoint sources of pollution, mine-related sources of pollution, and construction sources of pollution as well as set forth procedures and methods (including land-use requirements) to control, to the extent feasible, such sources. It is further mandated that point sources be identified and controlled.

A better understanding of the coupling of drainage basin characteristics, meteorological events, and human activities with water quality will provide the basis on which to make better management decisions. For example, the construction of higher technology waste treatment plants is frequently thought of as a sound approach to the problem of maintaining or improving the water quality of an aquatic ecosystem. In some cases, this may be an inappropriate course of action because the major nutrient input comes from nonpoint sources; perhaps the emphasis should be placed on controlling the nonpoint source inputs. In other cases, the water may be naturally of poor quality and currently available management practices of little avail. More soundly based management decisions should reduce monetary waste and at the same time improve or maintain the quality of the nation's inland and near-coastal surface waters. Although some work has been done on this problem, it is generally restricted in geographic extent, with much of the emphasis being placed on water quality in streams.

Numerous parameters (e.g., soil type, slope, land cover, precipitation intensity, trophic indicators) will need to be measured and/or estimated to develop the necessary predictive models. Some of the data can only be or are best collected through the use of remote sensors. The technology needed falls into two categories:

(1) Remote sensors - aircraft- or satellite-borne

(2) Interactive geo-referenced based data processing system - such a system should permit the storage, retrieval, and analysis of a variety of data (e.g., photographic, map, multispectral scanner, demographic, water quality, morphometric). It would permit the exploring of hypothesized coupling relationships and lead to the development of models and information necessary to answer the above questions.

The technology exists, at least in a quasi-operational mode.

C. Movement of Particles From Rural Lands

The land is a source of sediments, water, and natural and manmade pollutants. Pollutants originating on the land are eventually found in rivers, lakes, estuaries, and in oceans. Transport processes on rural land surfaces can be illustrated best by soil erosion. The basic processes on erodible lands are:

- Detachment of particles, controlled by rainfall energy on the land surface and soil erodibility. Vegetation cover changes detachment by intercepting rainfall energy. Farming changes soil structure and increases erodibility. Erodibility is time variable and is changed by the process of armoring, i.e., the selective erosion of fine particles that leaves coarse particles on the surface.

- Movement of particles over the land surface, controlled by overland or sheet flow. Detached particles are transported by moving water, where the energy available to move particles depends on the depth and velocity of flow. Overland flow depends on soil properties (soil depth, infiltration capacities) and on the weather. One storm may cause overland flow that will transport as much as 90 percent of the sediment eroded in a year. Soil properties, vegetal cover, and land slope vary over the land surface creating hydraulically active areas that can dominate watershed behavior.

- Transport in streams formed by rainfall, controlled by flow depth and velocity. These streams appear in fields and swales during rainfall and flow into small creeks. They erode soil forming rills and gullies on logging roads, firebreaks, and in construction areas. Stream beds are armored by selective movement of sediment by particle size. Deposition of sediments occurs in areas of low velocity or in ponds.

Adequate predictive capability does not exist for erosion of particles from the land surface, although extensive work has been done on the problem. The transport process varies in time and from point to point on the watershed surface. The lack of a solution to the problem stems from a lack of basic data and methods for handling data on erodibility, vegetal cover, soil properties, and forest and agricultural operations. The amount of data is so large that better management schemes are needed to make data available for analysis.

Linkages between particle erosion from the land surface and delivery to estuaries are not fully understood. Important phenomena are an apparent reduction in transport, and a reduction in the mean particle size during transport as watershed size increases. Quantitative data on atmospheric fallout of particles onto the land surface are not, as yet, adequate. Effects of alternate agricultural practices on erosion have not been fully explained.

Modeling of watersheds can be initiated with field studies. An example might involve a 10 to 50,000 km^2 watershed where remote sensing is used to obtain a data base of land use, vegetal cover, agricultural practices, and forest management. The data base would include both permanent land surface features like forests and lakes, and transitory features like cropping patterns, forest cutting, snow depths, soil moistures, and surface heat exchange. Remote sensing would be integrated into model calculations to follow movement of sediment and pollutants. The model results would be used directly in planning land use, energy production, water resource management, and forest management. The following specific requirements are listed in order of need:

Data	Parameters	Spatial scale	Time scale
Land use	Vegetation; forest density and type water surfaces; topography	5 hectares	Six months
Forestry, agriculture	Crops; forest harvesting; tillage	2 hectares	Monthly
Heat balance	Net radiation exchange	50 hectares	Daily
Snow surface	Areal coverage	50 hectares	Daily
Soil properties	Temperature; moisture at surface	5 hectares	Daily
Water properties	Temperature; sediment content; biological activity	0.05 hectare	Twice daily

D. Movement of Particles From Urban Lands

The process of particle generation from impervious urban areas (asphalt/concrete roads and parking areas) differs from erosion. The amount of solids originating from impervious surfaces depends on their accumulation rate, cleaning practices, and availability for pickup by runoff.

1. Particle Accumulation. Primary sources of particulate matter include atmospheric fallout, litter, vehicular effluents, and road breakdown.

Atmospheric fallout represents a significant portion of particles accumulated on impervious surfaces. It may contain some toxic pollutants (PCB's, lead, and other metals). The amount of atmospheric pollutant fallout at a given site is a function of the proximity of air pollution sources, meteorological, and other factors. Generally, atmospheric fallout can be related closely to land use (i.e., it is lower in low density residential areas and higher in industrial and high density urban areas).

A portion of the atmospheric fallout may not originate from within the drainage basin. Particles from sources outside the basin can be delivered to the receiving waters through the atmosphere as a result of dry deposition and/or precipitation. If these sources are urban areas or industrial centers, a river draining an otherwise pristine basin may carry significant amounts of pollutants attached to particles. At the present time, there is essentially no information on the importance of this transport. Although it is known that certain components of the dissolved load of a river may not be the result of weathering in its drainage basin (e.g., Cl, F, Na), no estimates of the portion of pollutants similarly derived have been made.

Litter arises from solid wastes (food, paper, plastics, rubber, metals, etc.) disposed of by the public and from activities of pets. The litter component has a larger mean size (3.2 mm) than do dust particles (less than 3.2 mm in size), but the latter may originate from the disintegration of litter particles.

Traffic impact, through the breakdown of road surfaces, is another source of urban particulate matter. The road particulates also contain high amounts of lead; however, traffic is also a source of other pollutants such as organics (tire wear, oil, and grease), chromium, asbestos, and phosphates. Traffic impact depends on road conditions (refs. 31 and 32).

Most of the urban particulate matter (over 95 percent) can be found within 1 m from the curb or median barrier (ref. 32). Because of that, most of the loading figures for urban particulate matter are reported in g/m of curb and not as areal values.

Particle accumulation rates have a tendency to level off after several days of dry period due to translocation of particles by wind and traffic action on adjacent pervious areas serving as sediment traps (ref. 32).

Street cleaning practices are selective mostly for coarser litter particles and ineffective for finer particles containing most of the pollutants. Overall efficiency of street sweepers is around 50 percent but drops to about 10-20 percent for fine fractions (ref. 32).

2. <u>Washout of Particles Into Receiving Waters</u>. Availability of particles for pickup by rain and their subsequent surface movement on impervious urban areas is related to the amount of rainfall, the slope and surface texture as well as the particle size. Over a prolonged period of time, almost all the particles accumulated on the surface which were not transferred to adjacent pervious areas or lost by degradation and sweeping will eventually end up in receiving waters.

A significant amount of research has been devoted to urban particulate matter problems. In spite of that, there are still some gaps, which include: Origin of particulate matter and the contributions of the various sources; particle size distribution; pollutant association with particles; particle washout process; accumulation model; and remedial measures.

Several large EPA (Environmental Protection Agency) projects presently deal with pollution from urban areas. It is believed that within several years the problem will be understood to a sufficient degree to enable EPA to propose and undertake proper remedial measures and significantly reduce urban nonpoint source pollution.

Presently EPA is proposing to study urban nonpoint source pollution and remedial measures (ref. 33). The research involves: (a) Accumulation rates as related to land use and other factors; (b) effect of remedial measures such as street sweeping, street flushing, sediment traps, retention barriers, and treatment of storm waters; (c) characteristics of urban sediments such as particles and contamination; (d) washout of particles (selectivity of storm runoff for various particles and pollutants); and (e) sources of urban pollution.

The most important parameters for estimating particle loadings and movement from urban impervious areas are as follows: Surface characteristics (i.e., percent impervious, percent grass, etc.); percent of areas directly connected to surface waters (e.g., roads and driveways connected to sewers or ditches as compared to roofs and other areas overflowing on adjacent pervious areas); curb length per unit area; frequency of sweeping and type of vehicles used for sweeping; atmospheric pollution and contamination; traffic density; road conditions; land use (residential, commercial, industrial, transportation, etc.); vegetation (trees); and rainfall rate and distribution.

The major drawback in present technology of nonpoint source pollution studies is the data base and its acquisition. Land characteristics are usually obtained manually from outdated maps and aerial photographs. The accuracy is low and often important information can be missed. For example, construction sites which contribute the largest amounts of sediments in urban areas are often poorly characterized (or missed) due to outdated land characteristics information. Often areas which are shown as nonurban have been converted to urban land use within a period of 1 year or less.

Remote sensing can assist in gathering some of the most significant and difficult to obtain information related to the pollution generation from urban nonpoint sources. Remote sensing is almost essential for adequate and accurate evaluation of the magnitude of nonpoint source pollution and its impact on receiving waters. The information obtainable by remote sensing include: Parameters with long-term variability - mapping, land-use inventory and identification, imperviousness of the area, surface character and condition, curb (road) density, and vegetation; and parameters with short-term variability (hours) - traffic volumes, atmospheric pollution and fallout, and storm paths.

E. Movement of Particles in Rivers

Once sediment moves from the land into the river system, the percent of the material which is actually transported downstream continues to be a significant question. For example, lake-like widenings and impoundments may result in loss of some of the sediment load. Material may also be deposited on flood plains during high water periods. The transmission from point sources, particularly those located considerable distances upstream from the receiving water, is also poorly understood. These questions are of considerable consequence, since a major problem currently facing the nation is nonpoint source pollution and the means to control it. Knowledge of these processes would lead to more cost-effective controls of tributary or coastal river pollutant loads.

The following is a list of specific questions related to river transport processes:

(1) What are the major deposition sites for particulates (and associated pollutants in rivers)? To what extent are materials transmitted (i.e., delivered) from upstream to river mouth sites?

(2) What is the frequency and extent of the resuspension of the sedimented material?

(3) Time of travel of sediment (and associated pollutants) in river systems is often poorly understood, particularly on the larger systems. How soon do all materials which enter a river eventually reach the receiving water?

(4) Since for many rivers, large percentages of the annual loads of tributary transported pollutants are contributed during storm events, it is important to have tributary flow and concentration data during these episodes. Since storm event sampling is expensive and logistically difficult using present techniques, can methods be developed to obtain this information more efficiently?

(5) Point sources may enter rivers at various places. How do these sources interact with the river system and are their pollutants transported to the receiving body of water? In what time period?

(6) Many rivers, particularly large rivers, have complex and dynamic flow-velocity contours that affect the transport of pollutants. How can these be determined and what is their importance to the transport of pollutants?

(7) What is the significance of the material transported along the river bed? This material may be in the form of a slurry or floc layer and may concentrate certain pollutants.

(8) How can we get better information on estuarine physical processes? For example, what is the effect of seiches on material transport?

(9) Can the types of sediments found in rivers be characterized in order to ascertain their source? This would provide information needed to identify the major contributing areas or hydrologically active areas in need of control.

(10) How can we measure progress in the clean-up of the nation's rivers? It is important to be able to demonstrate clearly and simply the effect of clean-up efforts. Also, how can new spills or pollution problems be cost-effectively detected. Overall, there is a need for better systematic monitoring, possibly linking detailed sampling with less detailed, more synoptic information.

(11) Another major research problem is the "biological availability" of pollutants associated with particulate material transported by rivers to lakes or oceans. What portion of the pollutant (nutrient, heavy metal, or other toxic substance associated with particulate material) can be taken up by biological organisms or can affect biological processes? Information on the biological availability of pollutants from different sources is needed to determine where pollutant control programs can be most effective.

F. Movement of Particles in Wetlands

Four fundamental types of wetlands influence the transportation processes of sediments from the continents to the oceans: (1) Swamp, (2) riverine, (3) lacustrine, and (4) estuarine. Swamp wetlands occur in low areas within the drainage basins, including small lakes and ponds, and along flood plains. Riverine wetlands persist within the flowing portions of streams. Lacustrine wetlands are associated with the coastal waters of large, deep lakes, such as the Great Lakes. Estuarine wetlands are found in the mixing zones between freshwater tributaries and oceanic waters.

Wetlands are thought to function in several ways to modify the processes of sediment transport. Primarily, wetlands serve as sediment traps and wave attenuation structures. These functions tend to reduce the amount of suspended particles that would have been transported in the absence of wetlands. Wetlands may or may not serve as permanent sinks for sediments, associated contaminants, and organic materials.

In order to better understand the functions of wetlands in the process of sediment transport from the continent to the oceans, a number of research questions need to be answered:

(1) Within a drainage basin, what is the areal extent of swamp and riverine wetlands?

(2) What is the quantity of land runoff materials trapped within swamp wetlands?

(3) What is the quantity of stream-transported materials trapped within swamp and riverine wetlands?

(4) Under what conditions are materials suspended and dissolved and released from wetlands, and what are the quantities of these releases? What new materials are formed in wetlands and released to the surrounding waters?

(5) Do seasonal cycles in vegetation growth affect the sediment trapping and wave attenuating abilities of wetlands? What is the annual primary production in wetlands? What is the species composition of wetlands?

(6) Do excessive amounts of suspended particles limit the vegetative growth in wetlands and thereby negate their sediment trapping and wave attenuating abilities?

(7) What is the areal extent of swamp and lacustrine wetlands associated with coastal areas of large lakes?

(8) What is the quantity of sediment particles originating from tributaries and nearshore wave resuspension which are trapped within coastal wetlands of large lakes?

(9) To what degree do coastal wetlands of large lakes attenuate the force of wave attack and reduce the resuspension of sediment particles?

(10) What forces are required to negate the wave attenuation abilities of coastal wetlands or destroy them as viable vegetative wetlands?

(11) What is the influence of water level on the sediment trapping and wave attenuating function of wetlands?

(12) What is the areal extent of estuarine and marine coastal wetlands?

(13) What is the nature and quantity of material cycling between estuarine/marine coastal wetlands and nearshore oceanic water masses?

(14) To what extent has human activity modified the natural functions of coastal wetlands, such as dredging, filling, and diking?

G. Movement of Particles in Lakes

1. Current Predictions. The problem of predicting the currents in a well-mixed lake is the simplest and most basic problem in predicting particle transport. All other modeling depends on this capability. The objective is to predict the time-dependent, three-dimensional wind-driven currents throughout the lake.

The conceptual understanding of this problem is relatively good. Mathematical models are available but the parameters centering into these models need improvement. Verification of these models has been limited.

The major problems are (a) predicting the wind stress over the lake from knowledge of winds on shore and (b) determining the bottom shear stress and eddy coefficients as a function of the flow, topography, wave conditions, and wind stress.

Further verification of these mathematical models is needed. For this, extensive measurements of currents and wind stresses are required, at approximately 10-km intervals. Bottom shear stress measurements (Reynolds stresses due to turbulent fluctuations) are also needed. Winds are presently measured at shore stations and do not permit accurate extrapolation to the lake surface. At present, current measurements are inadequate for verification. Shorter-term (3-4 day events) calculations should be used for verification and long-term (several months) calculations are needed in applications.

2. Transport of Particulate Matter Including Resuspension and Deposition. Particulate matter is transported vertically to the sediment-water interface by a combination of turbulent diffusion and settling. A characteristic time for diffusion is $h^2/2A$ while a characteristic time for settling is h/w_s (where A = Eddy coefficient; h = Local depth, and w_s = Sediment particle velocity). In shallow waters (where $h \leqq 2A/w_s$), turbulent diffusion dominates. The manner in which particulate matter is deposited and entrained at the sediment-water interface depends on the applied bottom shear stress due to waves and currents and various factors descriptive of the sediments. Among these factors are water content, mineralogy, grain size, sediment deposition history, and activity of benthic organisms. Some major problems are: a quantitative description of resuspension and deposition rates and the dependencies of these rates on shear stress and sediment parameters; the relative effects of major storms versus milder wind events occurring many times over the year; resuspension of dredge disposal; and deposition of sediments in shipping channels.

Our understanding of and our ability to quantitatively predict resuspension and deposition rates are relatively poor. Mathematical models describing the transport of particulate matter and sediments throughout the lake system are in a preliminary stage. A serious problem is our limited quantitative knowledge of bottom shear stresses due to the combined effects of waves and currents and the variation of type of particulate which occurs throughout the Great Lakes.

Bottom sediments represent a major source and sink for many contaminants, e.g., nutrients, trace metals, and organic compounds. An understanding of the flux of contaminants across the sediment-water interface is the key to predicting contaminant availability. Since many contaminants adsorb readily onto the surface of particulates, especially fine-grained clay particles, a general knowledge of particulate transport would be a major step toward predicting the ultimate fate and availability of contaminants.

Research needs are as follows: Laboratory experiments on resuspension and deposition rates determining their dependence on major governing factors; field measurements to determine bottom shear stress as induced by wave action and currents; and mathematical modeling of whole lake transport coupled with field verification including surface mapping of organic and inorganic particulate concentrations.

For mathematical modeling of sediment transport, the following parameters are needed: Wave height or adequate wave hindcasting models, wind stress over a 10-km spatial grid, resuspension and deposition rates determined from laboratory experiments for site-specific sediments, wind stresses, current velocities as calculated by models, and surface particulate concentrations as input data on 1-km grid for whole lake problems and less for nearshore problems.

Mathematical transport models need to be verified by comparison with field data. Short-term verifications (3-4 day events, especially during strong winds) and long-term (several months) applications and verifications should be made.

3. Transport of Contaminants in a Thermally Stratified Lake. Thermal stratification strongly affects the currents and vertical turbulent mixing. As a result of these changes, the biochemistry of certain regions of the lake may be drastically altered. For example, Lake Erie is strongly stratified during the summer and the hypolimnion goes anoxic. When this happens, large fluxes of nutrients, trace metals, and perhaps other contaminants are released from the sediments and are then transported through the hypolimnion, perhaps entering the nearshore and the epilimnion. During the fall when the thermocline erodes and eventually disappears, large fluxes again may occur due to the fact that wind-induced turbulence may now penetrate to the bottom where before it was inhibited by the stratification.

Additional significant scientific problems related to thermal stratification are: (a) A valid description of the formation, maintenance, and decay of the thermocline; (b) a comparison of vertical transport *vs*. horizontal transport especially as it affects transport from the hypolimnion to the epilimnion and transport in nearshore upwelling and downwelling areas; (c) onshore, offshore mixing especially as inhibited by horizontal thermal gradients; and (d) understanding of and capability for predicting transport in thermal plumes from power plants and rivers into lakes. Basic to all of these problems and an area in which much work is needed is a better knowledge and description of turbulence in a stratified flow.

The currents, turbulence, and hence the transport of contaminants in a stratified flow are not well understood. A valid quantitative description of the thermal structure in a lake by means of a mathematical model has not been made. Of course, a major problem is our inadequate knowledge of turbulence in a stratified flow. Of equal importance is the lack of synoptic temperature data, i.e., surface temperature maps to describe areas of upwelling and downwelling, and vertical profiles throughout the basin to describe the thermocline structure and its variation in time and space. Accurate knowledge of wind stress variations over the lake surface is extremely important for calculation of currents and thermocline motion.

In order to analyze this problem properly, extensive field measurements, coupled with mathematical modeling, need to be carried out. If a sufficient data base for currents, wind stress, wave height, and temperatures is available, then by means of mathematical models and comparison of the observed and calculated data, a considerable knowledge of turbulence in a stratified flow can be obtained. This knowledge can then be used to better predict currents, temperatures, and transport of contaminants in other situations.

The basic whole lake mathematical models for predicting thermal structure, currents, and particulate transport are now available and need to be applied to specific lakes and events. Of course, although the models are available, this does not mean that the parameters that go into these models are quantitatively known. For verification of these models, extensive current data need to be obtained. Of even more importance are adequate temperature data: Vertical temperature profiles at various points throughout the lake, surface temperatures with approximately 1-km resolution at daily intervals in the open lake and 0.5-km resolution in the nearshore where upwelling occurs, wind stress, wave height, organic and inorganic particulate concentrations, and heat flux.

H. Movement of Particulates in Estuaries

Estuaries are regions where river water meets sea water. It is here that both the substances in the suspended load and bed load of rivers, which are in equilibrium or quasi-equilibrium with river water and which are largely responsible for the adsorption of many pollutants, meet a different aqueous chemical environment. The nutrient elements N and P may be poorer or richer in river water, and complex organic compounds (such as vitamin B_{12}, biotin, and thiamin) which phytoplankton may require for growth may or may not be present in appropriate amounts or ratios for marine algal growth.

As a generalization, kinetic factors dominate over thermodynamic factors in the estuarine zone with gradations in both chemical and biological species from fresh through brackish to salt waters.

Estuaries may be very productive biologically or can be virtually sterile. For example, the Amazon estuary is characterized by huge diatom blooms, while the Congo River estuary shows none. Both rivers are poorer in N and P than the ocean.

The estuarine zone often is the site of precipitation of hydrated iron oxides which are very strong adsorbers of metals and many other pollutants. The river clay mineral fraction, which contains most of the metallic pollutants, may "flocculate" at the sea/river interface and be carried in a strong flow along the sea bed. Much of its heavy metal load may redistribute itself in the precipitating iron oxides, and hence "fix" in the nearshore sediment.

Estuarine marshes are often sites of intensive photosynthetic carbon fixation - much of the carbon appears to be in the form of a carbonaceous "slime" - the product of microbe/plant symbiosis. The consequences of this form of carbonaceous "particle" for inorganic, organic, and biological reactions are not yet clear.

Estuarine recycling is considered to be of major importance. Rapid changes in chemical conditions due to saltfingering, storm flows of river water, etc. may serve to mobilize some elements and plant nutrients with attendant biological fluctuations.

River plumes may remain observable by chemical or physical means for considerable distances, depending upon current systems and density of load. The Amazon northern plume may extend 1000 km and is of major importance to coastal fisheries because of its algal bloom. The location of the Mississippi plume in relation to the Gulf loop current is of major importance to the oceanic fate of pollutants transported in this river.

Many estuarine processes and plume dynamics can be studied by tracing the distribution of suspended matter (turbidity). Such studies, however, require temporal and spatial resolution not easily obtained by "standard" oceanographic field techniques.

I. Movement of Particles Along the Continental Shelf

The movement, deposition, and resuspension of suspended particles along the continental shelf - whether originating from rivers or stormscour of the coastline and shelf bottom - is intimately linked to the movement of continental shelf waters. If the movement of the water is unknown, it will be impossible to address the suspended-particle question. Qualitative understanding exists for various forcing mechanisms of shelf waters: Tides, steady and impulsive (storm) winds, offshore features (meandering Gulf Stream and associated ring movement), alongshore features (whatever is happening on adjacent coastal areas), variations in river flow, and bathymetric influences. Quantitative understanding, however, is only possible when a large effort (many ships and moored instrument systems) is devoted to a specific site; this is necessary for obtaining synoptic observations of the current velocity and density field - which in turn enables the separation and identification of spatial and temporal gradients. A good example is the recent MESA program in the New York Bight.

A quantitative understanding of the movement of shelf waters is required when addressing (1) the location of dredged channels and the fate of dredge spoil; (2) the location of sewage and industrial outfalls and the fate of outfall products; (3) the location of nutrients and plankton, and the possible association of fish; and (4) the location of offshore dump sites and the fate of dumped products.

The work required in enabling a realistic attack on this problem involves combined ship-borne, moored, and remote (both satellite and aircraft) instrumentation - measuring current velocities, temperature and salinity (therefore density) structure, winds, and other parameters (e.g., ocean color). Remote observations are required for broad areal coverage of surface and near-surface conditions; ship and moored observations are required for assessing temporal variability as well as for determining how well the 2-D surface features can realistically portray the 3-D subsurface structure.

Much of the work required involves advances in observational instrumentation: Development of ship-borne profiling (sensing temperature, salinity, and currents) gear capable of underway deployment, development of moored gear capable of long-term profiling, development/assessment of airborne remote profiling gear, and an assessment of satellite products in conjunction with such parameters as surface winds, waves, temperature, salinity, color, and height.

J. Movement of Particles Across the Continental Shelf to the Continental Slope and to the Abyssal Plains

For an understanding of the particle movement across the continental shelf to the continental slope and abyssal plains, there is needed a time-varying 3-D knowledge of the current velocity and density field, especially the low-frequency or mean component, which is buried in the following "noise":

(1) Tidal (oscillatory)

(2) Wind-generated (impulsive)

(3) Surface wave

(4) Offshore - gulfstream meanders and rings

(5) Longshore - coming from adjacent regions

(6) Bathymetric/topographic - turbulence

The near-bottom currents are essential to understand resuspension, especially from storms. Spatial and temporal variabilities must be ascertained. This implies synoptic observations. We now are working on improving the following observational tools and techniques:

(1) Land-based - radar (surface only)

(2) Moored - current meters and profilers - under development (fixed points)

(3) Ship mounted - profilers ($\vec{v}$ and ρ) under development (slow moving)

(4) Drifters - need satellite tracking

(5) Remote observation buoys - surface only

(6) Bottom mounted - under development (fixed points)

Advances in understanding - and therefore our capability to model - is limited at present by poor observational capability. Surface currents can be modeled slightly. Oil spill offshore, for example, cannot be modeled in these dimensions. We do know that particles settle on slopes and in canyons at shelf-slope break. We do know that turbidity currents remove this sediment and deposit it on deep sea abyssal plains. Yet, we have never directly observed turbidity currents.

V. GLOBAL GEOCHEMICAL PROBLEMS

A. The Problems of Sinks for Atmospheric Carbon Dioxide

1. Statement of Problem. Atmospheric CO_2 is increasing by about 1 ppm per year. The current level is about 335 ppm; it is generally agreed that 100 years ago the level was about 280 ppm. For some time it was thought that this increase was entirely the result of additions from the burning of fossil fuels and from cement manufacture, and that the rest of the carbon cycle has been in steady state. Such a model leads to the conclusion that about 50 percent of the CO_2 that has been added from these anthropogenic sources has remained in the atmosphere, and 50 percent is elsewhere. The two chief sinks postulated were the ocean (35 percent) and the terrestrial biosphere (15 percent).

The amount taken up by the ocean was calculated by assuming that atmospheric CO_2 maintains equilibrium with the surface waters of the ocean, and is mixed downward slowly into deeper waters. Furthermore, it has been assumed that the increase in CO_2 in the water is controlled only by solution of the gas, without reaction with any solids. The chemical system involved is

$$CO_{2\,(atmosphere)} \rightleftharpoons CO_{2\,(dissolved)} =$$

$$H^+_{(dissolved)} + HCO^-_{3\,(dissolved)} \rightleftharpoons H^+_{(dissolved)} + CO^=_{3\,(dissolved)}$$

When atmospheric CO_2 increases, the reaction results in an increase in dissolved CO_2 and a decrease of dissolved $CO_3^=$. The increase of dissolved HCO_3^- is at the expense of $CO_3^=$ according to $H_2O + CO_2 + CO_3^= = 2HCO_3^-$; so, the carbonate alkalinity, $HCO_3^- + 2CO_3^=$, remains constant.

Most models have assumed that CO_2 dissolves as above, without any reactions with solids, because the mixed layer of the ocean is commonly considered to be supersaturated with the common shell materials, calcite and aragonite. Both are $CaCO_3$; because of a difference in crystal structure, aragonite is somewhat more soluble.

In the model being presented, the 15 percent of the missing CO_2 not in the ocean was supposed to go into the terrestrial biosphere, perhaps encouraged by CO_2 stimulation of forest growth and by storage in eutrophied lakes and rivers.

The picture presented held until a few years ago, when more careful consideration of the terrestrial biomass indicated that it is much more likely that it is decreasing, as a result of deforestation and oxidation of soil organic material, than increasing. Suddenly the oceanic sink appeared inadequate. Today is a time of reassessment of the carbon cycle. The date for doubling of CO_2, by extrapolation of existing data, is about 2050. If the sinks should fail to continue to operate, that time might come much sooner. If they improve their performances, the time might come much later. Most modeling indicates that doubling atmospheric CO_2 would lead to a $2^o - 3^o$ C global temperature rise, with little change in the tropics, but with warmings of 8^o C or so at high latitudes. Current concern is with possible shifts in climatic regions; long-term concerns are for melting of the icecaps.

So today it has become of great importance to understand the carbon cycle in all its aspects. As before, the terrestrial biomass and the ocean are major targets.

2. The Ocean as a Sink for CO_2. A major effort will certainly be made to extend the work on tritium and ^{14}C as tracers to understand mixing of the surface ocean with deeper waters. This work involves chiefly vertical profiling. What are some of the other variables that must be considered?

The possibility exists that reactions of dissolved CO_2 with carbonate materials are taking place. These reactions may either be chiefly with calcite and aragonite in the more undersaturated waters of high latitudes, or they may be with high magnesium calcites in intermediate and low latitudes. It has recently been reported that carbonates are actively being dissolved over an area of 100,000 km^2 in the region of the Skaggerak (refs. 34 and 35). The general "sink" reaction is:

$$H_2O + CaCO_3 + CO_2 = Ca^{++}_{(dissolved)} + 2HCO^-_{3(dissolved)}$$

Dissolution increases carbonate alkalinity. If the surface ocean had continuously maintained chemical equilibrium with a carbonate mineral by dissolving it as atmospheric CO_2 increased, the ocean would be three times as effective a sink as calculated with the constant carbonate alkalinity model. Calculations indicate that the "carbonate equilibrium model" would result in a 10-percent increase in carbonate alkalinity to accompany the change of CO_2 in the atmosphere from 280 to 335 ppm. The increase in carbonate alkalinity is roughly proportional to ${P_{CO_2}}^{1/2}$ (where P_{CO_2} is pressure of CO_2).

For the ocean, we need to:

(1) Measure the degree of saturation of surface water globally with respect to carbonates.

(2) Monitor globally the carbonate alkalinity of surface water.

(3) Estimate downward mixing by methods that will reinforce ^{14}C and tritium studies.

Another possible significant sink for excess carbon in the oceans is an increase in the flux of organic carbon into deep water or to burial in sediments. Fertilization of the oceans by increased fluxes of phosphorus and nitrogen increases biomass, and hence the carbon withdrawn from the system. This process is not restricted to the oceans; it occurs in rivers, lakes, estuaries, and perhaps most of all in the coastal zone. For this carbon flux, we also need to:

(4) Monitor the freshwater and ocean biomasses.

(5) Monitor dissolved organic carbon.

(6) Assess recent and past carbon deposition rates in coastal marine sediments.

The six tasks listed seem to be some that are important to accomplish if the relation of the carbon cycle to increasing atmospheric CO_2 is to be understood and if successful predictions are to be made. They are by no means all of the investigations that could be proposed, but they have high priority. In the following section the role, or possible role, of remote sensing will be discussed.

3. Remote Sensing Applications to the CO_2 Problem. In the preceding paragraph, six possible areas for application of remote sensing were suggested. There are a number of possibilities for application of remote sensing techniques to assessment of the magnitude of the oceanic sink for CO_2 produced by the burning of fossil fuels and other cultural activities. The remote sensing applications to the CO_2 problem fall into two categories - those involving remote sensing techniques currently available and those necessitating some developmental effort. These two categories are discussed below.

4. Information Obtainable Utilizing Currently Available Remote Sensing Techniques. (a) Productivity and biomass - Although the productivity of the oceans (and lakes) is nutrient limited and the marine biomass is only about 1 percent of the total biomass, excess nutrients added to the oceans and other aquatic systems may stimulate productivity. Increased productivity can lead to increased biomass which, in turn, can result in increased sedimentation of organic matter. Organic matter that sediments to the bottom of marine and lacustrine regions and is not recycled from the sediments to the overlying water columns represents stored carbon. It has been estimated that industrially produced CO_2 stored in sedimentary organic material could be comparable to the amount of combustion carbon as yet unaccounted for (ref. 36). This is certainly an upper estimate but the magnitude of this sink needs to be evaluated.

Chlorophyll measurements from remote sensors using visible light spectrometry could provide the necessary data to estimate global marine (and lacustrine) biomass. If these chlorophyll measurements can be obtained over a period of time, then estimates of global marine productivity, a poorly known quantity, can be made. The frequency and distribution of the chlorophyll measurements will depend on the temporal variability and spatial distribution of production. In particular, coastal marine areas and regions of upwelling are critical to evaluation of global marine productivity, biomass, and possibly of sequestering of combustion CO_2 as carbon in sedimentary organic matter. The open ocean is most important for assessment of total marine productivity.

Furthermore, because of (1) the link between marine productivity and production and possible consumption of dissolved organic matter (DOM), and (2) because some CO_2 produced by cultural activities may end up, at least temporarily, in the DOM or particulate organic matter reservoirs in the oceans, it is critical to determine the concentration and distribution of DOM in the ocean. Presumably, this can be accomplished by remote sensors at the same time as the chlorophyll measurements are obtained.

(b) Global distribution and temporal variation of oceanic surface temperature and salinity - It is necessary to know the global rate of downwelling (conversely upwelling) to assess the rate at which CO_2 mixes downward in the oceans. Geochemical techniques involving ^{14}C and tritium analyses of seawater samples lead to different conclusions concerning the rate at which fossil fuel CO_2 may penetrate the main thermocline of the ocean.

Globally distributed temperature and salinity data obtained from the surface of the ocean by remote sensors can be used to obtain a more complete picture than is currently available of regions of downwelling and upwelling and their geographic distribution and temporal variability. The temperature and salinity data should be tied into the currently available surface and subsurface chemical data of GEOSECS to enable as complete an interpretation of vertical and horizontal transport as is possible.

(c) Global oceanic surface currents - Horizontal movements of currents are important in mass transport processes in the ocean. With respect to CO_2, it is important to know the current field at the surface of the ocean and its temporal and spatial variations. This information is necessary for assessment of the magnitude and rate of mixing of CO_2 between coastal regions and the open ocean. Also, the generation of large vortices on the oceanward sides of the great "rivers of the sea" (e.g., Gulf Stream, Kuroshio Current) and their mixing with waters of the central gyres of the ocean may be important in horizontal transport and mixing of CO_2 in the ocean. This information on global current patterns should be obtainable by remote sensors, making high-altitude altimetry measurements. Obviously, this method could be extremely efficient and rapid in comparison to the standard oceanographic techniques of obtaining surface current patterns and their temporal variability.

(d) Global distribution and temporal variability of "whitings" - "Whitings," suspended inorganic precipitates of $CaCO_3$, have been observed in lakes and, perhaps, in the oceans. Indeed, the spatial distribution of whitings was observed and mapped by remote sensing techniques in several of the Great Lakes. The presence of whitings indicates that the surface of the water body in which these precipitates form is supersaturated with respect to $CaCO_3$. It may be possible to monitor the occurrence and distribution of whitings in aquatic systems, particularly lakes, over several decades by remote sensing techniques. The idea is that combustion CO_2 dissolving in lakes will lower the saturation state of the water and, perhaps, lead to a change in the occurrence of whitings. They may totally disappear if the lake waters become undersaturated because of uptake of CO_2. Thus, the occurrence of whitings can be used as an indirect measurement of the saturation state of lake waters and may be useful in assessing the impact of culturally generated CO_2 on the chemistry of lake waters.

5. Information Requiring Some Development of Remote Sensing Techniques.

(a) Remote sensing of HCO_3^- and $CO_3^=$ - The HCO_3^- and $CO_3^=$ ion concentrations of seawater are currently about 0.0024 mole liter^{-1} and 0.00026 mole liter^{-1}, respectively. If CO_2 emitted to the atmosphere by the burning of fossil fuels and other cultural activities enters the oceanic mixed layer and reacts with particulate carbonates, then the alkalinity of seawater will increase. Most of this increase in alkalinity will be related to the HCO_3^- ion in solution. We anticipate that if reactions of CO_2 with carbonate minerals occur in the ocean, the HCO_3^- concentration of seawater will increase about 2 percent in 10 years.

Measurements of the HCO_3^- ion content of seawater on a global scale over a period of 1-2 decades will show whether or not the HCO_3^- content is increasing. If there is an observed increase in HCO_3^-, then carbonate minerals must be dissolving as CO_2 is added to the oceanic mixed layer.

Measurements of $CO_3^=$ concentrations at the same time and place as the HCO_3^- measurements are made will enable calculation of the pH, $CO_{2(aq)}$, total alkalinity, carbonate alkalinity, and saturation state of the water with respect to carbonate minerals. The saturation state of surface seawater on a global scale is especially critical and of fundamental importance to our concepts of the chemistry of the sea. If over a period of a decade or two, the pH of mixed-layer ocean waters decreases but the carbonate alkalinity remains constant, it is likely that culturally generated CO_2 entering the mixed layer does not react with suspended carbonate minerals.

Remote sensing of the distribution of HCO_3^- and $CO_3^=$ concentrations in the oceanic mixed layer and their temporal variability, perhaps utilizing Raman spectroscopy, would be a major contribution to our knowledge of the magnitude of the ocean sink for fossil fuel CO_2. To evaluate changes in HCO_3^- concentrations and the magnitude of the CO_2 sink in the oceans, it will be necessary to monitor these concentrations in the major surface water masses of the oceans at yearly intervals over a period of a decade or two. The time scale is important because potential changes in HCO_3^- concentration will occur slowly.

(b) Saturation state of high-latitude oceanic mixed-layer waters - Little information is available on the saturation state with respect to carbonate minerals of high-latitude ocean waters. This is critical to interpretation of the geographic position and magnitude of the mixed-layer sinks of CO_2. Petrographic data (refs. 34 and 35) have shown that in some high-latitude cold waters, a variety of carbonate minerals is currently dissolving. Berner (refs. 37 and 38) argues that northern high-latitude waters are undersaturated with respect to aragonite, and suspended aragonitic skeletons of pteropods in these waters may react with CO_2 entering the waters.

Whatever the case, one region of emphasis for remote sensing of HCO_3^- and $CO_3^=$ should be high-latitude, mixed-layer waters. With HCO_3^- and $CO_3^=$ concentration data, the saturation state of these waters with respect to carbonate minerals can be determined and the potential for these waters to act as a sink for culturally generated CO_2 assessed.

B. The Volatile Metal Problem

1. Statement of Problem. The measurement of metal fluxes to the atmosphere, on a global basis, from the sea surface, from volcanos, from surface rocks, and from vegetation is needed to understand the metal burden of the atmosphere. The relative enrichments of these metals over their values in crustal rocks appear to be nearly uniform over the Earth's surface although the concentrations of a given element may vary markedly from place to place. The sources of these metals in the atmosphere are yet to be identified. The elements enriched in the atmosphere are those that are volatile themselves or have volatile compounds. Conventional wisdom indicates that these metals have natural, as opposed to anthropogenic, sources. Further, the speciation of the elements is unknown for nearly all elements. Yet, such knowledge is essential in understanding the atmospheric processes involving these elements. The processes of removal of these species from the atmosphere, whether by wet deposition (washout) or by dry fallout, are as yet poorly quantified.

The SEAREX program (Sea-Air Experiment in International Decade of Ocean Exploration) of the National Science Foundation is currently investigating the metal concentrations of the atmosphere (in particulate form), the removal mechanisms, and their fluxes from the sea surface. Finally, the speciations of metals introduced to the atmosphere should be determined separately for each major source.

The relative contributions of natural and anthropogenic inputs to the atmospheric burdens of these metals can provide the regulatory agencies such as EPA and DOE with a scientific basis to evaluate potential hazards. The data may be of interest to epidemiologists from National health agencies, for instance, who seek relationships between the geographic occurrences of disease and environmental factors.

2. Needed Research. First of all, laboratory studies of fluxes from forested and vegetated areas should be carried out to identify the speciation of the heavy metals which exude from growing plants. Once the species are identified, the seasonal fluxes should be sought from major forests and vegetated regions. Laboratory flux measurements of the metal species issuing from crustal rocks and soils at temperatures from ambient to 1000° C should be determined. Field measurements on plumes from volcanos and fumaroles and controlled flux measurements on soils and rocks should be carried out. Laboratory fluxes from still and agitated seawaters should be made with emphasis placed upon identification of the volatile species and the roles of microorganisms and bubbles. Field studies can follow in marine environments of high and low productivity at different seasons of the year. Finally, an assessment should be made through the field program of the transport (i.e., distillation) of these volatile species from mid- to high-latitudes. This will require measurement of regional washout and fallout fluxes with emphasis upon deposition in the marine environment.

3. Techniques, Available and Needed. The laboratory and field approaches will be considered separately inasmuch as they involve distinct technologies. For the laboratory, laser induced fluorescence and ionization of gaseous species appear promising for concentrations of the order of 10^6 - 10^8 atoms/cc. As yet, there are no publications on the determination of atmospheric levels using these techniques. A literature study of the fluorescent time decay from a multiplicity of energy states might reveal a potential use for this technique. Such a method might be useful for multimetal mixtures. The present development of copper and copper halide lasers should be investigated for the measurement of copper species in the atmosphere.

C. The Measurement of the Isotopic Composition of Surface Waters

The $^{18}O/^{16}O$ ratios of surface waters contain a record of evaporation and precipitation processes for water masses. These processes are important in the world's water and heat budgets. Thus, a knowledge of their values on a global basis would be most useful in climatic and geochemical studies. At the present time there are very few such measurements being made by chemists because the analyses of small numbers of samples by mass spectroscopy do not enhance our present knowledge significantly. However, regional or global coverages could provide a novel basis for understanding heat and water fluxes in greater detail.

Remote backscatter Raman spectroscopy holds promise for the measurement of this ratio. There is possibly a measurable isotopic band shift and/or band shape distortion as a consequence of these isotopically different waters. The ratio of $H_2\,^{18}O/H_2\,^{16}O$ is about 1/2000. Differences of parts per thousand in the ratio would reveal evaporation/precipitation patterns.

VI. CONCLUDING REMARKS

This volume presents the results of a Workshop on Remote Sensing and Problems of the Hydrosphere sponsored by the NASA Office of Space and Terrestrial Applications and the Langley Environmental Quality Projects Office. Major scientific problems in water quality are identified and discussed, and, in many instances, suggestions are made on how remote sensing can contribute to their solution. These results will be used by NASA in the development of long-range plans for research and development activities on coastal processes.

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APPENDIX

LIST OF ATTENDEES AT NASA WORKSHOP ON

"REMOTE SENSING AND PROBLEMS OF THE HYDROSPHERE"

January 29-31, 1979 - Warner Springs, California

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Rosewell Austin
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Luther Bivins
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Richard Blackwell
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APPENDIX

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15. Supplementary Notes

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16. Abstract

This volume presents the results of a Workshop on "Remote Sensing and Problems of the Hydrosphere." The Workshop, which was sponsored by the NASA Office of Space and Terrestrial Applications and the Langley Environmental Quality Projects Office, was held January 29-31, 1979, at Warner Springs, California. The participants were organized into four working groups: Bioprocesses, Gas and Aerosol Fluxes, Particle Fluxes to the Aquatic Environment, and Global Geochemical Problems. Major scientific problems in water quality have been identified and discussed, and, in some cases, suggestions have been made on how remote sensing might contribute to their solution.

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