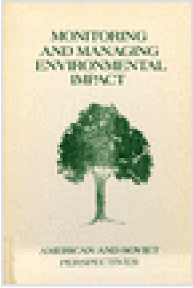

Monitoring and Managing Environmental Impact: American and Soviet Perspectives (1988)

Pages
291

Size
5 x 9

ISBN
0309319978

Glenn E. Schweitzer and Anna S. Phillips, Editors; USSR State Committee for Hydrometeorology and Control of the Natural Environment; US Environmental Protection Agency; US National Academy of Sciences

Soviet-American Symposium on the Comprehensiv
Analysis of the Environment (5th : 1986 : Washin
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Monitoring and Managing Environmental Impact: American and Soviet Perspectives

Proceedings of the Fifth US-USSR Symposium
on
Comprehensive Analysis of the Environment

December 10–13, 1986

Glenn E. Schweitzer
Anna S. Phillips
Editors

USSR State Committee for Hydrometeorology
and Control of the Natural Environment

US Environmental Protection Agency

US National Academy of Sciences

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Available from:
Soviet and East European Affairs
National Research Council
2101 Constitution Ave., N.W.
Washington, D.C. 20418

Printed in the United States of America

Preface

At the request of the US Environmental Protection Agency (EPA), the National Academy of Sciences hosted a US-USSR bilateral symposium December 10-13, 1986, in Washington, D.C. on the topic "Comprehensive Analysis of the Environment." The meeting was fifth in a series of symposia on this topic and was part of an ongoing project within the framework of the intergovernmental Agreement on Cooperation in the Field of Environmental Protection between EPA and the USSR State Committee for Hydrometeorology and Control of the Natural Environment (Hydromet). Lee M. Thomas, Administrator of EPA, and Yuriy A. Izrael, Chairman of Hydromet, who serve as co-chairmen of the Joint Committee which oversees this agreement, also served as co-chairmen for the Symposium. A complete list of participants appears in Appendix 1.

The Symposium's goal was to help clarify the various factors which influence the quality of the environment, including the impact of pollutants on the ecosystem and human health, the influence of human activity on the biosphere, and the scientific basis for determining ecological resilience. A general session addressed approaches and basic concepts, while technical sessions covered such topics as monitoring approaches and technology, regional-scale case studies, management applications, and global monitoring strategies. Future directions for joint research were discussed at the closing session. A brief overview of the technical sessions introduces and provides a context for the papers presented at the Symposium. The official protocol of the meeting appears in Appendix 2.

Interpretation services provided by Natalie Latter, George Markov, and Dwight Roesch during the Symposium are gratefully acknowledged, with particular thanks to Mr. Roesch for his assistance in translating the Soviet presentations for this publication. Financial support from EPA and the John D. and Catherine T. MacArthur Foundation is also acknowledged and appreciated.

The views expressed in the individual presentations which follow are those of the authors, and do not represent the views of any official organization or agency.

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Overview of Technical Sessions

GLENN E. SCHWEITZER
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The Fifth US-USSR Symposium on Comprehensive Analysis of the Environment was intended to contribute to an understanding of the influence of human activities on the biosphere and, more specifically, of the impact of pollutants on ecosystems and on human health, thereby improving the scientific and technical basis for developing a broadly-based strategy for monitoring and managing the environment.

The Symposium was held against a background of extensive international, bilateral, and national discussions and program activities directed to very similar topics. On the international scene, UNEP, WMO, UNESCO, FAO, SCOPE, and ICSU are among the many organizations which have been very active in these fields over the years. Indeed, one of the challenges facing participants at the Symposium was to draw on these past efforts in framing future global approaches. With regard to bilateral activities, the Symposium provided a forum for bringing together results of many past and current US-USSR joint activities, thereby adding greater coherence to individual projects. As to national activities, both the US and the USSR have initiated a number of efforts in recent years to broaden perspectives concerning long-term effects of human activities on the environment. A comparison of approaches undertaken by the two world leaders in environmental sciences was therefore seen as particularly timely.

MONITORING APPROACHES AND TECHNOLOGY

During the first technical session of the Symposium, a number of relatively new monitoring systems were discussed. In each case, the techniques were directed toward monitoring large areas; for example, in the case of snowpack monitoring, the area of interest encompassed most of the USSR. Similarly, in the case of monitoring lakes susceptible to acidification, large areas of the United States were of interest. Considerable attention was also devoted to the monitoring of areas which are not easily accessible. The use of helicopters, airplanes, and even horses for data collection was discussed.

Emphasis was placed on operational monitoring systems, but in each case a considerable degree of experimentation and adaptive research was involved. The importance of refinements of the original designs of the monitoring networks was highlighted. The spacing of sampling stations, the frequency of sampling, and the size of the region of interest (such as the area selected around Lake Baikal) were all seen as elements of crucial importance. Several advanced laser monitoring technologies were also discussed.

Interpretation of monitoring data is not always straightforward. Sometimes the data are most useful as inputs to models. On other occasions the monitoring data are used alone in drawing concentration isopleths, which in turn may be related to sources.

Unfortunately, time did not permit a discussion of Soviet and American methods for chemical analysis, nor were details of quality assurance programs, and particularly the statistical aspects of such programs, considered. However, there was general recognition of the importance of the quality of monitoring data that are collected in different countries.

REGIONAL-SCALE CASE STUDIES

The second technical session considered several types of activities, with an emphasis on monitoring activities conducted over vast areas. Many of the concepts discussed, including sampling design and use of advanced monitoring technologies, were closely related to discussions during the first session.

Preliminary reports were presented on the 1984 joint US-USSR expedition in the Bering Sea. Concern was expressed over the levels of contamination encountered in areas of the world's oceans which had been previously considered relatively pristine. There was a clear consensus that this joint activity was an outstanding example of true collaboration and that future cooperation should build on such past successes. Continued monitoring of the Bering Sea was seen as particularly important since it could serve as a baseline area in monitoring the overall condition of the world's oceans.

The use of biological monitors along the US coast was reviewed, and the importance of continuing such efforts to provide trend information on the condition of coastal areas was emphasized.

The use of large models to help determine the dispersion of air pollutants received considerable attention. Comparisons of modeling and monitoring results were seen as important in the continuing effort to improve air dispersion models. The difficulty in relating climatic changes to resource impacts on a regional basis was underscored.

MANAGEMENT APPLICATIONS

The third technical session considered how policy makers in the United States and in the USSR can most effectively use scientific results in controlling discharges of pollutants into the environment. A very difficult aspect of determining control strategies is predicting the impact of controls and, still further, accurately assessing this impact once the controls are in place. There is great interest in both countries in relating monitoring measurements in urban areas to specific pollution sources. However, this task is often difficult in view of the many sources that may be discharging similar pollutants as they move through the environment.

During a lively discussion of ecological risk assessment, the role of the scientist throughout the decision-making process was debated. The view was expressed that there are no good measures of ecological damage and that the impact of pollutants is often addressed too narrowly. There is a need to ensure that risk assessments are placed in the broadest possible context, taking into consideration long-term changes which result from impacts on biological species from the lowest to the highest order. Scientists provide a unique perspective on such long-term effects which cannot be ignored in management decisions.

The ecological importance of soil resources and the susceptibility of soil to anthropogenic impacts are often underestimated. Change in the soil covering of the earth is usually a slow process; and discerning such change, though often very difficult, is of critical importance. Three different types of soil monitoring should be considered: global, regional, and impact monitoring. A good start has been made internationally in preparing maps on the types and distribution of soils, and consideration should now be given to the development of soil preservation mapping, perhaps beginning with determination of alkalinity and acidity conditions.

Finally, the debate over the control of acid rain in the United States was seen as a good example of the difficulty in making enviromental management decisions with very large financial implications when there is great scientific uncertainty regarding the extent of near-term and long-term impacts of pollution.

GLOBAL MONITORING STRATEGIES

The wide variety of papers presented in the fourth and final technical session underscored the wide range of efforts in the United States and the USSR to improve understanding of anthropogenic impacts on a global scale. Several papers addressed the conceptual problems in assessing and predicting climatic impacts of discharges into the environment of sulphur dioxide, carbon dioxide, and nitrogen compounds. The effects of discharges of chlorofluorocarbons on the ozone layer continue to be of great concern. Studies have been initiated to predict the effect of climatic changes on agricultural, forest, and coastal resources, and on human health. Also of concern is the continued heavy reliance throughout the world on pesticides and the lack of adequate attention paid to the drift of pesticides away from targeted areas during application from aircraft.

Other papers presented the results of specific monitoring programs. Coordinated Soviet and American measurements of chlorofluorocarbon and carbon dioxide levels from ship-based and land-based stations showed excellent agreement. The importance of standardized monitoring protocols has been demonstrated in these activities. Soviet programs for monitoring microbial reduction of sulphur compounds in bottom sediments were also discussed.

Finally, the development of integrated background monitoring stations in the United States and Chile as a step toward development of a worldwide network of such stations was described. Initial plans were outlined for a monitoring system for the International Geosphere Biosphere Program (IGBP) currently being developed under the auspices of ICSU. These presentations sparked a spirited debate on the concept of global monitoring, and particularly the need to integrate land-based and sea-based monitoring activities. The importance of building upon and not duplicating past international efforts was emphasized. There was some uncertainty as to how monitoring efforts under IGBP would differ from the current activities of WMO and existing national systems.

In conclusion, the concept of ecological risk assessment was seen as quite complex. In the past, efforts toward solving immediate localized pollution problems may have diverted attention from the issue of how human activity is changing ecosystems on a broader scale. Technology has provided us with many tools for monitoring environmental changes. Now the challenge is to effectively utilize this technology to monitor the most critical indicators of changes which significantly impact on the biosphere. Given the limited resources available for this enormous task, effective international pooling of resources is not only desirable, but essential.

Long-Term Monitoring of Acidification Trends in Lakes: A Regional Perspective

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Likens (1983) noted that establishing long-term, high quality monitoring programs may represent the highest priority in environmental research. Well conceived and well designed long-term monitoring maximizes the likelihood of detecting and understanding subtle environmental changes in ecosystems.

There may be no clearer example of the benefits of historical monitoring records than those associated with acidic deposition and its effects, particularly those relating to changes in the chemical quality of surface waters. At the same time, however, the acidic deposition experience in North America also has revealed many limitations in using historical data bases to detect trends in surface water acidification. Recognition of these limitations can be used to design more effective long-term monitoring programs in the future.

Changes in the acidity of surface waters in North America have been reviewed by Church (1984) and most recently by Kramer et al. (1986). The conclusion in both of these reviews—and in the numerous research articles which provided the basis for the reviews—is basically the same: some surface waters in the United

States, most notably those in the northeast, have lost acid neutralizing capacity within the past 50 years. However, even ignoring the obvious questions related to the mechanisms of acidification and the magnitude of change (e.g., the role and contribution of acidic deposition in this process), there is still considerable uncertainty surrounding this conclusion. This uncertainty involves the reliability of the trends themselves as well as the geographic scale and number of systems within the total resource to which the trends apply. These issues provide a basis for investigating some common, if not universal, limitations in the use of long-term monitoring data that decrease or sometimes negate their utility.

This paper reviews the limitations associated with previous trends studies and proposes an approach to long-term environmental monitoring which would facilitate regional-scale assessments.

HISTORICAL PERSPECTIVE OF ACIDIFICATION TRENDS

As noted by Kramer, a significant deficiency in the interpretation of historical surface water quality data lies in the documentation of sampling and analytical procedures. In the case of acidification trends, for example, the procedures for measuring pH and alkalinity have changed from colorimetric to electrometric methods. Although it would appear relatively easy to compare the two methods and to adjust historical and/or recent data accordingly, the lack of a clear definition in the historical records relating to the color change of the methyl orange indicator used for alkalinity titrations has been a major point of debate.

Before 1950, the terms used to describe the end point of the alkalinity titration were "pink," "faintest pink," "very faintest pink," "fainter pink," and "salmon pink" (Kramer). Although the debate continues due to a lack of definitive evidence, the weight of information suggests that these descriptions of color change probably correspond to a range of pH values between 4.0 and 4.2. When evaluating trends, a difference as small as a few tenths of a pH unit can result in an alkalinity variation of 10 to 20 ueq/L. Consequently, depending on which end point pH in the alkalinity titrations is chosen as the most accurate for historical colorimetric alkalinity data, the change in alkalinity from past to present has been reported to range from quite large to quite small.

To complicate further the quantification of change from existing water quality records of the 1930s to the present, consideration must be given to the precision of the historical measurements. Using historical data, Kramer found that the variation in alkalinity values from duplicate samples collected on the same day was 53 ueq/L, representing both analytical and within-lake variations. Variability in duplicate samples collected on different days within the same season was approximately 67 ueq/L. If seasonal and yearly variability in alkalinity is considerable, this number could be still larger. Thus, a difference in alkalinity of less than 67 ueq/L from past to present would not necessarily be convincing evidence of change, and differences greater than 67 ueq/L may still be suspect because year-to-year variability is not considered. Episodic variability in lakes, for example, has been reported to be 200 ueq/L or greater (Driscoll and Newton 1985).

Another complicating factor in determining trends using historical data is the fact that any lake over a 50-year period can be subject to many natural and anthropogenic perturbations which can alter water quality. Consequently, to increase the certainty that a regional-scale change in acidity is occurring as a result of a common cause, many systems must be investigated and compared. Within the same area, depending on the particular lakes chosen for investigation, very different inferences might be drawn depending on the sample size and the types of analytical methods used. When data are used collectively from a number of systems (e.g., on a subregional scale) the response of a single lake is lessened in importance.

Although increasing the sample size will increase the confidence in the conclusion that a response has indeed occurred, a larger sample size will not necessarily ensure that the results reflect the collective response of the entire regional surface water resource. Kramer observed that of the lakes in New Hampshire which had experienced alkalinity changes greater than 100 ueq/L since the 1930s, 37 percent decreased in alkalinity and 63 percent increased. As the sample size in this analysis was only 11 lakes, conclusions for the response of the total surface water resource in New Hampshire must be viewed accordingly. Increasing the sample to 130 (as was done in the Kramer study in the analysis of New York lakes) might afford a better evaluation of the regional response; however, questions concerning the comparability of methods complicate data interpretation.

In this analysis, depending on which alkalinity titration end point is chosen to calculate the median alkalinity change, substantial increases in acidic status (based on pH 4.2) or no change (based on pH 4.0) would be concluded. Thus, while a change in any system may justify further evaluation, questions remain regarding sample size, methods, and regional representativeness of conclusions. This in turn fuels decision-making debates, particularly when the results within a region are inconsistent.

EXTRAPOLATION OF SITE-SPECIFIC RESULTS

Kramer raises a number of additional considerations relative to trends analysis which are critical to effective environmental monitoring. These issues are the importance of cation/anion balance data, internal consistency checks, and accuracy versus precision. While addressing such considerations is indeed critical to the proper design of a monitoring effort, one conceptual issue which is acknowledged infrequently in trends studies remains of paramount concern: regionalization of results or the applicability of conclusions to a region of interest. This concept includes quantifying variability among and within systems and the representativeness of statistically unbiased data collection.

Despite the increased availability of high quality data bases relative to those available in the 1930s, there has been virtually no way to characterize confidently potential trends in acidity over broad geographic scales. In the Kramer study, the median alkalinity of a group of lakes decreased, although some of the lakes in the investigated group increased in acidity. While the median change provided a regional perspective, the relationships of the lakes that decreased and those that increased to the total number of lakes in the area are not known. Therefore, the actual representativeness of the "regional" classification employed, although more informative than a single site, is still unclear.

In 1984 and 1985, the US Environmental Protection Agency (EPA) conducted a study of lake and stream water chemistry to establish a water chemistry data base that would provide a regionally applicable baseline. The study was implemented partly in response to the problems of detecting changes in acidic status of surface waters as outlined in the Kramer review and partly to address questions of regional representativeness. The primary questions to be addressed in the study were: What are the present acid neutralizing capacity (ANC) and pH of surface waters? What is the population distribution of these surface waters with respect to these two variables? Are there any regional patterns in ANC or pH? What are the physico-chemical characteristics of groups of surface waters in different ANC and pH classes? What will be the rate of change in the future?

The EPA study—called the National Surface Water Survey—was conceived as a three-phase investigation of lakes and streams potentially sensitive to change induced by acidic deposition. Each phase provided the statistical basis for its successor, permitting site selection to be performed in such a way that the results of an investigation of any subset of systems could be extrapolated quantitatively to a larger population of interest. Phase I was a synoptic chemical survey of a probability sample of systems drawn from a large number of systems located within relatively homogeneous geographic regions. Phase II was designed to estimate the magnitude of temporal variability in chemistry and to quantify biological resources. Phase III was a long-term monitoring effort focused on detecting trends in chemistry of regionally representative surface waters. This program is ongoing, with Phase I of the lake and stream surveys presently being completed. The results of the Eastern Lake Survey (Phase I), summarized in Linthurst et al. (1986), are presented here to illustrate the concept of regionalization and the importance of developing a fundamental basis for long-term environmental monitoring.

Site selection is an issue of primary importance to the design of a study for regional extrapolation of observed trends, which should be foremost in any long-term environmental monitoring program. While it is clear that the trends observed at a single site are of uncertain applicability to the region or to subpopulations of similar systems, regional applicability questions do not disappear simply by increasing the sample size. While increasing sample size undoubtedly increases confidence in the conclusions, the results may not be representative of the population as a whole.

Data from the Eastern Lake Survey are instructive in illustrating the importance of sample site selection, study design for regional-scale monitoring, and regional extrapolation. In this case, a stratified, random sampling approach was used in establishing baseline, regional-scale surface water chemistry. The smallest sample unit in this study was an alkalinity class (stratum) within a subregion of interest within a region, e.g., the northeastern United States. The results from unbiased site selection within a stratum allow comparisons to be made with sites in any other stratum. However, because an environmental issue of interest may not conform to the boundaries of the original sampling strata, the design is flexible enough to change the geographic boundaries of areas to be compared, i.e., the results from the alkalinity classes can be extrapolated to a whole subregion or region.

The results of such an extrapolation are shown for Acid Neutralizing Capacity (ANC) in Table 1. The median ANC values for the sample and estimated population are presented for four upper midwestern subregions and the Upper Midwest as a whole. Comparing the two columns of medians, it is apparent that they differ substantially, leading to quite dissimilar conclusions. The differences arise because the resource population within each stratum, now combined to represent a larger geographic unit (subregion), was not the same, i.e., the population of lakes within each original stratum is different. Different geographic areas can have different numbers of lakes; therefore, while every lake within a stratum is equivalent to every other lake, a lake in one stratum represents a different population size than does a lake in another stratum. This difference must be considered when extrapolations are made to geographic scales other than to the stratum level which frame the boundaries of the original sample unit. As demonstrated in the Kramer study, determination of the applicability of sample results to the resource population could not have been made had the population resource not been known (which is usually the case).

Once a resource base is established, comparisons among populations can be initiated. The distributions of ANC for the population of lakes in four subregions of the upper midwestern United States are shown in Figure 1, with the subregional populations exhibiting quite different ANC distributions. Thus, even based on this single factor analysis, different population responses might be expected. Because numerous other physico-chemical variables were measured during the Eastern Lake Survey, more complex, multivariate comparisons among populations can be made.

Subpopulations, as defined by any or all of the variables measured within the survey population, can be characterized for further research. More importantly, they can be used to determine whether lakes in ongoing site-specific studies represent the whole population. The advantage of classifying existing study sites within the population frame established during the Eastern

Table 1

Median values for Acid Neutralising Capacity (ueq/L) based on sample data and estimated population data for the Upper Midwest

Subregion	Sample Size	Sample Median	Estimated Population Size	Estimated Population Median
Northeastern Minnesota	150	145	1457	185
Upper Peninsula Michigan	146	97	1050	284
North Central Wisconsin	155	55	1480	94
Upper Great Lakes Area	141	134	4515	802
Upper Midwest	592	120	8501	360

Source: Linthurst et al., 1986

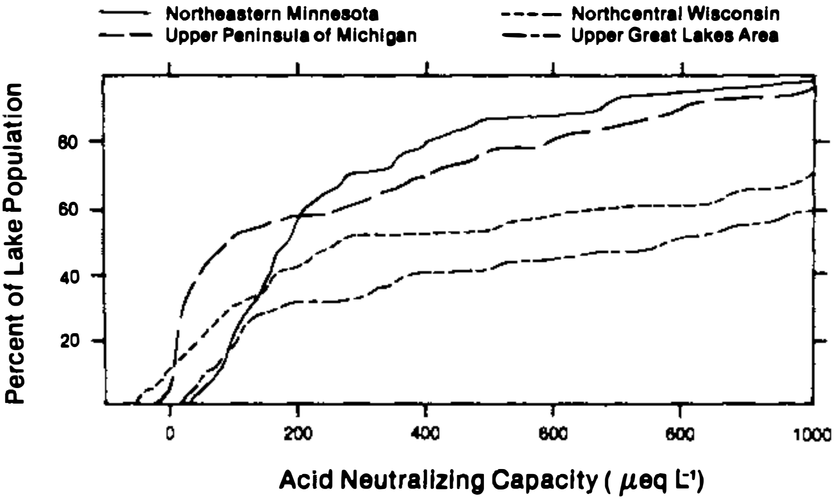

FIGURE 1 Comparison of cumulative frequency distributions for ANC for four Upper Midwestern (US) subregions (Linthurst et al. 1986).

Lake Survey is that many of these intensively monitored sites have considerable data records that can be used to assess trends.

Because the degree to which these intensively studied sites reflect the characteristics of the resource population can now be established, regional extrapolation can be accomplished. Thus, use of the Eastern Lake Survey data base to classify these systems may allow these site-specific data to be interpreted from a regional-scale, as opposed to simply a systems-scale, perspective. Further, contrasting characteristics of lakes on a population scale can rapidly advance understanding of the factors affecting change by recognizing the differences among lakes and identifying which ones are responding with what characteristics. The combination of intensive and extensive studies can therefore add considerably to both the understanding of a response and the regional applicability of the findings.

QUANTIFICATION OF ACIDIFICATION TRENDS IN THE FUTURE

Repeated sampling within the established resource base or within representative subpopulations can be used to predict future changes in acidity or other chemical characteristics of lakes. Figure 2 shows the 1984 ANC distribution (solid line) for the Northeast (Linthurst et al. 1986). The dotted and dashed lines represent two theoretical changes in the distributions of ANC that might occur in the future.

The certainty surrounding the original distribution is known. If the certainty surrounding the new distributions is also known, and if the expected temporal variability, the precision of the measurements, the analytical and sampling methods, and the physicochemical characteristics of the population are accounted for in the studies, the uncertainty experienced in Kramer's analysis should be minimized in the future. Furthermore, much could be learned about the cause of the theoretical changes by examining subpopulation responses.

It is expected that if acidification does occur, it will not occur uniformly over a region or within all lake types. Therefore, examination of population and subpopulation differences over time can contribute not only to quantifying change, but also toward understanding the factors which control the change. That is, by comparing lakes with differing responses and by recognizing their

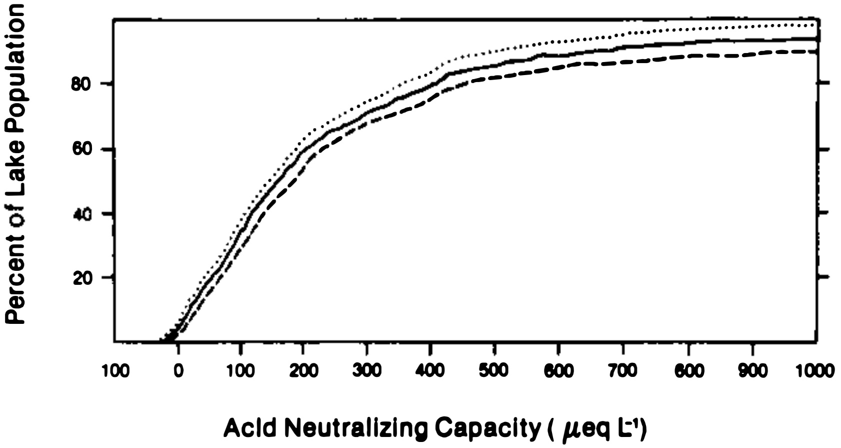

FIGURE 2 Distributions of ANC for the population of lakes in the northeastern United States. The solid line is the distribution estimated in the fall of 1984 (Linthurst et al. 1986); the dotted line is a hypothetical distribution which might be observed if the population of lakes exhibited a collective decrease in ANC; the dashed line represents such a distribution if the population exhibited a collective increase.

characteristics and those of the surrounding watersheds, much can be inferred about the factors which potentially control the changes. When these data are compiled with other environmental data, e.g., regional-scale deposition chemistry data over time, causal mechanisms for change can be proposed.

A discontinuous but repeated sampling schedule could serve the purpose of detecting future acidification trends. Inferential comparisons among subpopulations of surface waters will likely contribute to identifying the types of systems which respond or are at risk of changing. This approach will undoubtedly advance understanding of the factors controlling surface water response. However, the most complete understanding of surface water response and causes will result from a combination of coordinated extensive and intensive research, including the use of standardized measurement methods and of techniques to extrapolate site-specific conclusions to regional scales.

The experience gained in examining acidification trends, briefly and superficially reviewed above, provides an opportunity to improve substantially the ability to detect and understand subtle, long-term, environmental changes. The most notable conclusions based on this experience include:

- Careful and quantitative documentation of sampling and analytical protocols must accompany a monitoring program.
- Methods must be standardized, not simply standard, and any change in the monitoring protocol should be assessed carefully and calibrated quantitatively at the time of the change.
- Quality assurance of data, particularly with regard to calculating precision, is essential in environmental monitoring when change over time is the focus.
- Seasonal, yearly, and possibly daily or hourly variability must be known in order to have confidence in the detection of long-term trends.
- Studies of single systems, while important, are not adequate to detect or to understand fully regionally significant environmental change.

A long-term monitoring program designed and implemented today will obviously not be directly applicable to environmental issues 50 years from now. This has been illustrated by data obtained in the 1930s which were collected for purposes other than to detect acidification trends. In nearly all cases, the historical records are based on discontinuous, irregular point sampling data, collected for reasons unrelated to acidification. Therefore, this problem should serve as a reminder that any data collected today, irrespective of their relevance to acidification, should be flexible enough to accommodate or address potential issues in the future, and that there is no substitute for sound scientific technique.

Based on past and present experiences, future long-term monitoring should ideally include a coordinated, well integrated design and standardized methods for which precision can be quantified. A hierarchical approach to future monitoring appears best to address all aspects of the past and present issues. Such a design would be multi-tiered and based on infrequent regional-scale data collection. Built upon that base, and including fewer systems for which the relationship to the total population is known, would be subsets of lakes where temporal variability could be quantified and intensive site-specific research could proceed. Special studies at still fewer sites could be conducted at the fourth level as environmental issues change. The frequency of sampling would decrease as the number of systems studied increased, while the complexity of the studies would increase as the number of systems decreased in the hierarchy. Such a hierarchical approach—designed in terms of ecosystems rather than individual components—could serve as the structure to assess ecosystems at risk due to environmental contaminants on any scale.

The National Surface Water Survey is currently using such an approach, coupling studies of aquatic biota and soils within the established regional frame. All projects within the hierarchy use standardized methods and extensive quality assurance, and they are integrated to maximize the understanding of effects and regional applicability. By further coupling terrestrial and aquatic monitoring with air and deposition monitoring in a hierarchical design, much of the existing uncertainty about present environmental risk could be greatly decreased, and the basis for assessing future environmental risk would be well established.

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Monitoring Snowpack Pollution

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Scientists have long been attracted by the prospect of using snowpack to study environmental pollution. Work in this field, however, has generally been unsystematic, aimed instead at solving various specific problems. In order to systematically monitor the environment, researchers in the USSR have developed a snowpack pollution monitoring system based on an already existing network which measures the physical parameters of snow, i.e., snowpack height and density. This system generates an annual picture of the spatial distribution of pollutant deposition within the territory of the Soviet Union. This report discusses the scientific bases of monitoring snowpack pollution and its practical applications and includes a number of the latest findings obtained in recent years (1).

SNOWPACK AS AN INDICATOR OF POLLUTION AND ACIDIFICATION OF THE ENVIRONMENT

Annual global snowpack covers an area of 115 million square kilometers, reaching 125 million in some extreme years. This figure includes 79 million square kilometers in the northern hemisphere and 46 million square kilometers in the southern hemisphere. The continents account for roughly two-thirds of this snow-covered territory while the remaining one-third is distributed on bodies of ice at sea. With the exception of the southern reaches of the

Caucasus and Central Asia, the USSR regularly has snow cover over most of the country's territory.

Snowpack displays a number of properties which make it a convenient pollution indicator for contamination not only of atmospheric precipitation, but also of ambient air and of ensuing water and soil pollution. Snowpack can be used to quantify total pollutant parameters (wet and dry). While we can measure wet deposition with generally satisfactory results, a reliable means of determining dry deposition has yet to be developed. As a rule, the different techniques used so far have produced inconsistent results. A natural repository of both wet and dry deposition, snowpack reflects their actual value.

In the earth's mountainous and polar regions, snowpack is gradually transformed into ice, preserving any entrapped pollutants. They are stored in glaciers under favorable conditions for hundreds, even thousands of years, providing a unique chronicle of pollutant composition in ambient air. Snowpack is therefore an effective indicator of acidification processes in the environment.

Snowpack sampling is very straightforward, requiring no sophisticated hardware. Layer sampling provides a picture of pollution dynamics over the winter season: one single sample of the snowpack column will generate representative data on pollutants from the time a continuous snow cover is formed until the moment the sample is taken.

As snow forms and precipitates, wet and dry washout produce pollutant concentrations which are two to three orders of magnitude higher than those in ambient air. Therefore, relatively simple, yet quite reliable, methods can be used to measure these pollutant levels.

The amount of a pollutant precipitated over the duration of snowpack (to) for a unit of area (Q) is equal to:

$$Q = Q_w + Q_d = \int_{o}^{to} [c(t)p(t) + q(t)]dt \approx ncp + q(N - n) \qquad \{1\}$$

where Q_w and Q_d are wet and dry deposition; $c(t)$ is the concentration of pollutants in falling snow (and rain during warming periods); $p(t)$ is the rate of precipitation; $q(t)$ is the rate of dry deposition; N is the duration of snow cover in days; n is the number of days with snowfall; c and q are the mean daily concentration values in precipitation and dry deposition rates; and p is the average daily precipitation.

During periods of thaw and spring snowmelt equation 1 no longer holds true since a portion of the pollutants is removed with runoff water. There is also a reduction in snowpack moisture P_{sm} to a level lower than total precipitation P. However, as *in situ* observations have shown, measurements for pollutant concentrations in snowpack C_{CH} are frequently relatively low. Exceptions do exist, however, in instances where snowmelt is great. Value Q can then be derived for concentrations in snow and for measurements of the amount of precipitation at weather stations.

$$Q = Q_{sm} \cdot P/P_{CH} = C_{CH}P \qquad \{2\}$$

Equation 2 is pivotal to calculating winter deposition. It is more accurately applied to lightly polluted regions where the contribution of dry deposition is negligible.

The mean daily winter deposition rate from equation 2 can be described as:

$$U = C_{CH} \cdot P/N = Q/N \qquad \{3\}$$

The mass of pollutants precipitated during the winter period for area s over time t is expressed as:

$$M = t\int_s U(s)ds \qquad \{4\}$$

In actual practice, deposition for an entire year must be known. Equations 2 and 3 can also be applied to a snowless period by using the conversion coefficient:

$$U_{CH} = kU \qquad \{5\}$$

where k is defined by deposition rates in different seasons, with the chemical composition of precipitation measured over a relatively sparse network. Equation 5 is sufficiently accurate for regions which have either a direct proportionality between wet and dry deposition or low inputs of dry deposition. In most cases, such conditions are only disrupted in close proximity to emissions sources.

In early winter, before the formation of an unbroken snowpack, pollution of snow might occur from wind erosion of exposed soil parcels. This type of pollution diminishes precipituously as the snowpack builds, ceasing altogether with the formation of an unbroken snow cover. This factor operates for the entire winter in arid zones with low precipitation levels. Most soil particles are of large dimensions (50 mm or greater); these particles therefore determine local deposition Q_{melt}. The greater the ratio Q/Q_{melt}, the more accurately we can use snowpack contamination to describe the characteristics of humanly induced pollution and long-range transport from natural sources. Deposition Q_{melt} is negligible in all cases in the northern latitudes.

Snow water acidity is a function of the presence of free hydrogen ions. By disregarding weak organic acids and trace elements, we can express the concentration of hydrogen ions after a snow sample has been completely melted and dissolved as:

$$[H^+] = 2[SO_4^{2-}] + [NO_3^-] + [Cl^-] - 2[Ca^{2+}] - [K^+] -$$
$$-2[Mg^{2+}] - [Na^+] - [NH_4^+] + 2.5 \times 10^{-6} \qquad \{6\}$$

The residual component of this equation of 2.5×10^{-6} moles/l corresponds to the concentration of hydrogen ions in an equilibrious aqueous solution with a mean ambient carbon dioxide level of 330 million^{-1} and a temperature of 20°. The pH level which corresponds to this concentration is 5.6.

Increased hydrogen ion concentrations (low pH level) are generally observed as the sample begins to melt. According to equation 6, as aerosol particles dissolve and acids react with metal oxides, hydrogen ion concentrations diminish to asymptotic values. The initial hydrogen ion concentration denotes a possible value for the "acidic impulse," when a portion of the hydrogen ions is washed out with runoff during the spring snowmelt.

It follows from equation 6 that the pH level of snow water is dependent not on the absolute hydrogen ion values in solution, but rather on the difference between anion and cation concentrations.

SNOWPACK POLLUTION MONITORING IN THE USSR

The potential use of snowpack as an indicator of environmental pollution was the impetus behind the development in the USSR of a new type of monitoring: snowpack pollution monitoring. With this goal in mind, a transition was made from scientific research to systematic observations incorporating a network of snow parameter measurements. Snow surveys in the USSR are made using a network of more than 7,000 hydrometeorological stations and sites. The underlying principle of the survey process is a topographical, point-by-point investigation of the physical parameters of snow. This is achieved by looking at basic terrain features such as fields, woodlands, marshlands, and ravines. The focus of the snow survey is to obtain data on snow height, density, and moisture content in the area of a given station. Survey frequency during snow buildup is once every ten days. Snow density is measured using a snow weight gauge consisting of a tube with a beam balance. Snow samples are taken for the entire snowpack column. The sample is weighed, removed from the snow gauge, and not used again.

In order to determine the level of pollution in snowpack, we decided to preserve the snow sample and use it to analyze pollutant composition and concentrations. An overall description of the pollutants is obtained by analyzing a composite sample made up of several samples taken along the snow measurement route at points where snow density is measured. It was found that a single sample taken at the point of maximum moisture content in the snowpack just prior to the spring snowmelt sufficed for analyzing contaminants accumulated during the winter season.

The samples' aqueous and solid phases are separated by filtration during initial processing of snow samples at the meteorological station in order to prevent possible chemical reactions between matter dissolved in the filtrate and the solid precipitation particles. The filtrate can be preserved for up to 20–30 days with no significant changes in its chemical composition. Sample analysis is performed in Environmental Pollution Monitoring Laboratory Centers located in all of the regional administrations of the USSR State Committee for Hydrometeorology. It is also done in a number of major cities.

The snowpack pollution monitoring system, based on the snow measuring system of the USSR State Committee for Hydrometeorology, became operational in the USSR in 1980. It is currently part of the State Environmental Pollution Observation and Monitoring Service, and it includes observations at 1,000 meteorological stations. The network's density in the European USSR is one station per 8,000 km^2; for the country's Asian territory it is one per 3,000 km^2. Snowpack pollution is monitored over an area of 18.3 million km^2 (roughly 80 percent of the entire territory of the USSR). Measurements are made at every station for sulfates, nitrates, ammonium, and pH levels. Approximately 30 percent of the stations provide information on heavy metals and polycyclic aromatic hydrocarbons. The number of elements under study is constantly growing.

The monitoring project is aimed at providing a description of pollution in the USSR at large as well as in specific regions. The network also generates data on long-range and transboundary transport of air pollutants. In view of these priority issues, the observation network's greatest density is in highly populated industrial areas and along the USSR's western border. Approximately 40 percent of the stations measure pollution in and around major industrial parks and large urban areas. Another 40 percent monitor pollutant dispersion along the primary routes of pollution transport from industrial centers and regions. The remaining 20 percent track background pollution levels in specific areas of the country (including the Arctic basin). A 70-station network of observations on the chemical composition of precipitation is used to evaluate summer deposition according to equation 5.

Experimental research has demonstrated that observations of snowpack pollution are also effective in monitoring at the local level, e.g., in cities and near distinct emissions sources. For this reason, researchers have recognized the value of extending the monitoring system to different urban areas, incorporating existing environmental pollution monitoring centers. This subsystem is currently being implemented.

As will be demonstrated below, the snowpack pollution monitoring system can be used to tackle a number of key pollution monitoring tasks for which no other effective observation methods exist. Furthermore, the system has proven to be extremely cost-effective. Its development did not entail any additional labor resources or other outlays since it incorporates an already existing system of analytical laboratories and an observation network which gathers data on the physical parameters of snow. All of the basic sampling and analysis operations have been achieved by increasing labor productivity.

BASELINE INFORMATION OBTAINED FROM MONITORING SNOWPACK POLLUTION

Snowpack pollution data provide a range of essentially new information on pollution of the environment which was not previously available. These findings are discussed below.

Pollution Maps for the USSR

Annual snowpack pollution monitoring provides a spatial picture of pollution for the USSR, obtaining data which scientists previously considered beyond their capabilities. Pollution is broken down according to the following maps: (1) pollutant concentration in the snowpack at the point of maximum moisture content in the snow; (2) mean daily rate of pollutant deposition during the period of snow; (3) annual deposition; and (4) pH of value distributions. Similar maps are also being plotted for the entire area of the USSR on sulfates and nitrates. Maps covering heavy metals, benz(a)pyrene, ammonia, and other pollutants have been compiled for specific regions.

Sulfate and nitrate deposition rates over the country's European territory are clearly two to three and one-half times greater than for the Asian portion of the USSR. This is a function of industry distribution and pollutant input resulting from transport across the western border of the USSR. The highest concentrations were observed in urban and industrial centers, while the lowest were found in the USSR's Arctic zone. We found virtually no snowpack acidification for most of the USSR.

Elements of the Pollutant Balance in the USSR

The USSR's atmospheric sulphur balance was calculated using findings from systematic observations of pollution levels in the snowpack and airborne measurements of cross-border transport of air pollution in study (2). It was demonstrated that approximately 90 percent of the balance can be attributed to anthropogenic sulphur emissions. The most aggressive sulphur compounds are associated with man-made sources such as sulphur dioxide and sulfuric acid. At the same time, analysis of materials obtained in the snowpack pollution study indicates that the portion of nitrates of anthropogenic origin in the deposition is low, totaling 62 percent for the European and 36 percent for the Asian portion of the USSR. Annual sulfate and nitrate deposition in the USSR total 40 million and 18 million tons, respectively. Annual variations do not exceed 15-20 percent.

Patterns in Atmospheric Transport of Air Pollution

The direction and quantification of large-scale transport across the national boundary of the USSR, to the Arctic basin, and between specific regions are very important. Study (4) examines a method of determining sulphur compound fluxes across the USSR's western border; this method uses data on snowpack pollution along the border. It was determined that the flux into the USSR is equal to 4.2 million tons of sulphur per year, which correlates closely with data obtained using other measuring methods.

This study also evaluates the contribution to sulfate pollution in the Arctic polar regions from the USSR's central industrial zone, including the entire central belt across the European portion of the country and the Ural Mountains region. Industry of the Kola Peninsula and Noril'sk is also included. It was found that this contribution is less than 2 percent, with one-third of this amount attributable to transboundary pollutant fluxes across the USSR's western border.

Quantifying Air, Surface Water, and Soil Pollution

By incorporating newly developed techniques we can use snowpack pollution to generate data on pollutant concentrations in the air, pollutant abundance and concentrations in surface water, and pollutant accumulation in soil. In areas where no special observation system exists for these media, data from snowpack pollution monitoring are the primary source of information on environmental pollution. Data in study (1) on snowpack pollution indicate the following mean sulphur concentrations in ambient air, depending upon the remoteness of industrial release-points: 0.6 mkg/m^3 at distances equal to or greater than 1,000 kilometers; 2.0 mkg/m^3 at distances under 1,000 kilometers; and 4.0 mkg/m^3 at distances under 100 kilometers.

Study (5) evaluates the portion of sulfate input into a river system at high water vis-a-vis the total flux of sulfates in the river. It was found that this portion is 15-20 percent of the sulfate flux for northern river basins under background conditions in the USSR's European territory.

CONCLUSIONS

The scientific and methodological foundations have been laid for a new direction in monitoring the state of the environment: monitoring snowpack pollution. This project in the USSR incorporates an existing network which measures the physical parameters of snow and draws from the USSR State Committee for Hydrometeorology's network of Environmental Monitoring Centers. By increasing labor productivity, a snowpack monitoring system was developed which did not require additional manpower. The system functions at minimal cost in comparison with other forms of observations.

Further expansion of the snowpack monitoring project is under serious consideration. Ideas being considered include extending the monitoring network to urban and populated areas which lack air pollution monitoring systems and greatly expanding the list of elements under study.

Remote snowpack pollution monitoring techniques clearly hold tremendous potential. These include: (1) aerial and satellite observation methods for observing snowpack albedo; (2) use of airborne gamma methods to determine the moisture content in the snowpack of prairie lands; and (3) measurements of snowpack-induced solar radiation flow attenuation in mountainous regions.

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Airborne Laser Remote Sensing of the Environment

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In performing environmental assessments, measurements are made either over highly localized, site-specific areas or over large geographic regions which might involve a number of discrete sites of special interest. The term "remote sensing" as applied to environmental monitoring refers to the acquisition of environmental information without physical contact between the measured feature or parameter and the measurement sensor. There are obviously trade-offs which must be considered in choosing between traditional point-monitoring techniques or remote sensing, including the quality of information and the cost of obtaining that information.

Airborne remote sensing measurements are frequently employed to provide information over broad regions where the advantages of rapid, wide area, and nearly simultaneous coverage can be exploited. In addition, these systems typically can provide spatial coverage in time intervals that are consistent with the dynamics of pollutant transport, transformation, and depletion. For many applications, this technology provides the only opportunity to collect certain data sets.

Remote measurement systems can be characterized as either active or passive, depending on whether the system incorporates an energy source in performing the environmental interrogation. In active systems, some fraction of the transmitted energy from a laser or light source is scattered from or absorbed by the target, while in passive systems the measurement depends on the passive

Table 1

Applicable processes for remote sensing

Scattering	Rayleigh	Elastic	$f_l = f_d$	Lidar
	Mie	Elastic	$f_l = f_d$	Lidar
	Raman	Inelastic	$f_l \neq f_d$	Lidar
	Fluorescence	Inelastic	$f_l \neq f_d$	Fluorosensor
Absorption	Absorption due to vibrational, rotational, and/or electronic transitions			IR, visible, and UV DIAL

f_l = laser frequency
f_d = detected frequency

reflectance or surface emission of energy from the area of interest. Table 1 summarizes the scattering and absorption processes employed in laser systems and indicates the remote measurement methods which are based on these principles.

Design concepts, practical environmental measurement applications, and the direction of future developmental efforts will be discussed for several classes of remote sensing instruments.

LIDAR SYSTEMS

In order to investigate aerosol properties or quantify an atomic or molecular concentration, a laser source is located at some prescribed distance from a detector. Reflectors may be used in order to collocate both the laser source and the detector. Backscattering processes can provide range-resolved data by measurement of time delays in pulsed lidar systems. Diagnostic techniques include elastic (Rayleigh and Mie) and inelastic (Raman, near resonant Raman, fluorescence, and resonance fluorescence) scattering. Most aerosol studies have been of an experimental nature, and the problems associated with the inversion of spectral transmission, polarization, and scattering data to obtain size distribution and refractive index have yet to be completely resolved. The shape of the particulate material also must be taken into account.

Classical lidar devices are used to profile aerosol distributions in the lower atmosphere. Measurements are made by observing the relative back scattering of the intense, extremely short pulse of laser light as it interacts with suspended particles and molecules. Electronic analyzers monitor the elapsed time from firing the laser to the scattering returns and thereby "range" or measure the distances to the aerosol layers and the relative concentration of aerosol within discrete volumes within those layers.

The latest operational airborne lidar used by the US Environmental Protection Agency (EPA) is a two frequency system consisting of a neodynium-YAG laser transmitter, a 36-cm Newtonian telescope receiver, and an electronics package. This package provides for real-time processing and display of the range-resolved backscatter from aerosols between the aircraft and the ground and from the surface-reflected energy, both at the transmitted wavelengths. A flowchart of the system is shown in Figure 1. The two wavelengths, one in the green (0.53 um) portion of the visible spectrum and the other in the near infrared (1.06 um), are emitted simultaneously with a firing rate that can be varied between one and 10 Hz. At the maximum firing rate, and when combined with typical operational air speeds, a horizontal resolution of about 10 m can be obtained. With a laser pulse width of 20 nsec a maximum vertical resolution of three m is similarly obtainable, although the signal is usually digitized to yield a resolution of six m.

Some of the typical applications of lidars are:

- Determining the space and time variability of aerosol inhomogeneities;
- Assessing relative particulate concentrations;
- Measuring the vertical growth of boundary layers;
- Providing input to complex terrain and other atmospheric dispersion modeling efforts;
- Measuring plume opacity;
- Investigating the mixing of multiple boundary layers using a series of injected FDPs;
- Positioning an aircraft with *in situ* sensors in an air mass or plume.

One experiment to monitor the transport and dispersion characteristics of aerosol material over water was performed by SRI International (Uthe et al. 1985) and supported by EPA. A neodynium-YAG lidar similar to the one already described generated radiations at 1.06 and 0.53 um, the latter frequency via a frequency

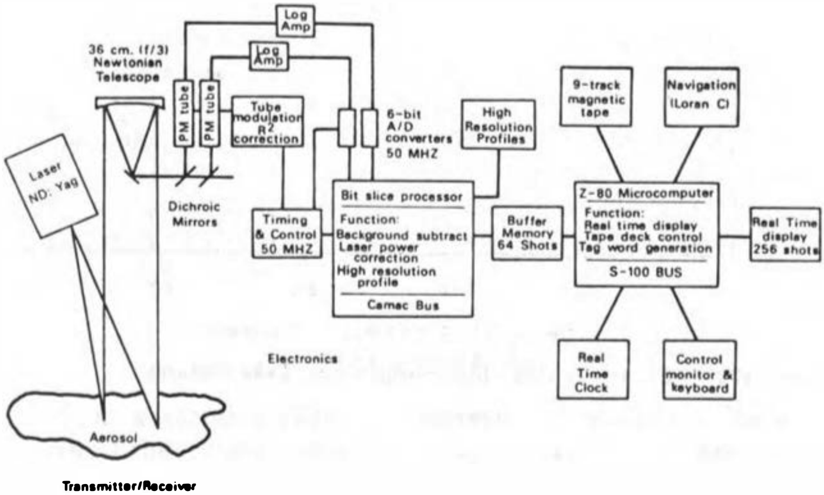

FIGURE 1 Airborne lidar schematic.

doubling crystal. The telescope receiver system was modified, however, to observe the aerosol elastic backscattering at 1.06 um as normal on one data channel while recording on the other channel the return at 0.6 um from fluorescent dyes injected into the atmosphere which emit at 0.6 um. The backscattered light at 1.06 and 0.53 um was rejected by the second independent receiver which permitted the system to map a fluorescent-dyed cloud and to study the atmospheric structure revealed by aerosol gradients.

A low altitude, fluorescent-dyed tracer cloud was released in the early morning hours over the eastern shore of Lake Ontario during conditions of easterly wind flow. The dispersion characteristics of the cloud were observed by the lidar system during its transport across the lake and its entrance over the Canadian shoreline. The behavior of the cloud near the land/water interface was also observed. Figure 2 shows the trajectory of the cloud

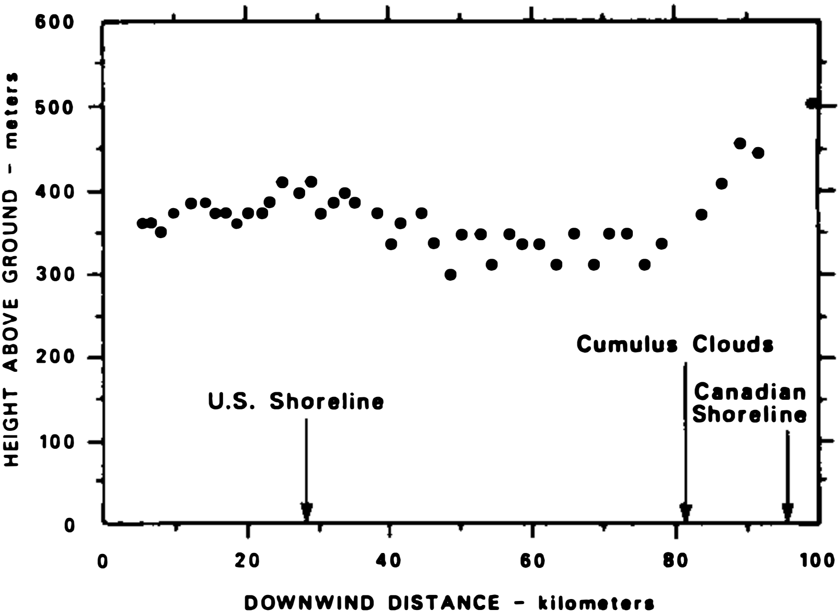

FIGURE 2 FDP tracer cloud observations over Lake Ontario.

during its transport period of approximately 95 km and 2.3 hours. The observed cloud height is presented as a function of transport distance. The altitude of the cloud was depressed over the water (vertical 1.5 cm/sec) and then rose sharply near the Canadian shoreline (vertical 10 cm/sec). The measured mean growth rate in the transverse direction of the cloud was reported at 27 m/min.

This study demonstrates the feasibility of monitoring the three-dimensional distribution of fluorescent dye particles during long-range transport and dispersion studies. Further, the study demonstrates the potential for using this technology to support research programs related to complex terrain modeling and to boundary layer transport and dispersion.

A second experiment used aerosols to study pollutant transport in the complex coastal environment of southern California (McElroy and Smith 1986). The wind flow regime in this region in the summer is dominated by a sea-breeze/land-breeze diurnal cycle. During late afternoon a relatively constant aerosol layer over the water and a second more dispersed layer at a higher elevation were observed. The two layers joined and mixed a short distance over the shoreline where the convective effect of onshore heating was clearly observable.

The double aerosol layer separated by a relatively clear layer over the water is frequently observed. The top of the lower layer corresponds to the base of the temperature inversion over the water while the upper layer exists within the inversion. Mixing occurs during onshore flow conditions when differential heating and mechanical turbulence over the land eliminate the layering. Pollutants from onshore sources can be transported in these elevated layers over the water with offshore breezes, only to be re-circulated onshore later and mixed downward to impact a shoreline area within the same or different air basin.

The significance of this phenomenon should be taken into account in the planning, siting, and development of new sources. Regional air quality models should consider the potential transport and downmixing of aged pollution which has been demonstrated through lidar studies.

DIAL SYSTEMS

In all absorption methods, observations are made at the wavelength of the incident radiation in absorption lines characteristic of the target molecules. Usually, a simultaneous or near simultaneous measurement is made at a nearby wavelength off the resonant absorption line to eliminate the need for absolute intensity measurements, i.e., a differential absorption measurement.

The differential absorption lidar uses two lasers very close in frequency output: one tuned to an absorption peak for a specific molecule and the other tuned off the absorption peak. The elastic scattering cross section is the same for the small wavelength change between the two laser pulses as they traverse the atmosphere, while the differential absorption cross section for the molecule being measured at the two wavelengths is known from laboratory measurements. The difference in the return signal is a direct measure, therefore, of the concentration of the molecular pollutant at that location in the atmosphere.

Potential applications of UV and/or IR DIAL systems are as follows:

- Cross plume mapping of organic tracers and gaseous criteria pollutants, e.g., [SO_2], [O_3], [NO_2];

- Measuring the atmospheric distribution of toxic air pollutants;
- Tracking the movement of organic materials accidently released into the atmosphere;
- Obtaining transport and diffusion data for use in the development and validation of atmospheric computational models;
- Measuring plume velocity.

Typically, UV DIAL systems would be used in the measurement of criteria pollutants while IR DIAL systems have the potential to measure a wide array of organic molecules.

An airborne UV DIAL system designed to measure ozone and aerosols has been tested by the US National Aeronautics and Space Administration (NASA) (Browell 1982) and has yielded results of the type displayed in Figure 3. The graph of altitude vs. concentration shows an excellent correlation between the profile measured with the DIAL system and that measured with *in situ* instrumentation on a spiraling aircraft, with both measurements taken in the same time frame. The lowest concentration measured (approximately 35 ppb) does not indicate the detection limit for this system but only the lowest level encountered. However, the sensitivity of the system is adequate for photochemical modeling and relates favorably to the National Primary Ambient Air Quality Standard of 120 ppb (maximum one-hour concentration). In practice, the system would provide a three-dimensional map of a measurable pollutant over the large geographical region of interest.

A compact UV DIAL system is being developed by EPA to simultaneously monitor from a small airborne platform concentrations of three criteria pollutants: SO_2, O_3, and particulates. An excimer pumped, Raman shifted laser system will be investigated for this application. The concept for this system is shown in Figure 4. Four wavelengths or Raman laser lines will be selected from the large number of simultaneously produced lines and monitors: three to provide data regarding O_3 and SO_2 concentrations and the fourth to provide information on particulate properties within the scattering volume. The simultaneous production of Raman laser lines permits the interrogation for each of the measurement parameters to be conducted in a single volume, while the nature of the atmosphere over the intervening path length is essentially constant.

This laser system has the additional advantage of including

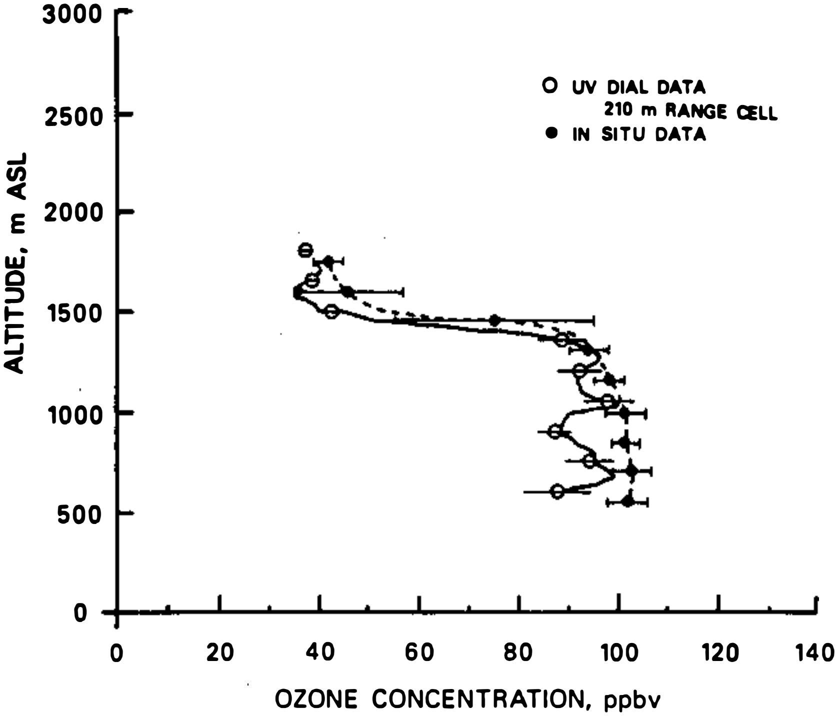

FIGURE 3 Comparison of DIAL and *in situ* O_3 measurements above and in the boundary layer.

few optical components and only two resonator mirrors which require precision alignment. In addition, the wavelength and the bandwidth of the excimer (KrF) and the Raman shifted laser emissions are known, constant, and independent of system performance. Many pollutant gases have absorption features in the IR spectral region (1–15 um). In addition, many other toxic and hazardous pollutants which are not normally found in other than trace amounts in the atmosphere have absorption features in this region.

The utility of an airborne IR DIAL system in mapping cross-plume vertical distributions of a near-surface released tracer gas (SF_6) has been demonstrated (Uthe 1986). In addition to providing the tracer detection for downwind transport and diffusion characterizations, this experiment demonstrated the potential of IR DIAL systems in mapping downwind distributions of toxic and

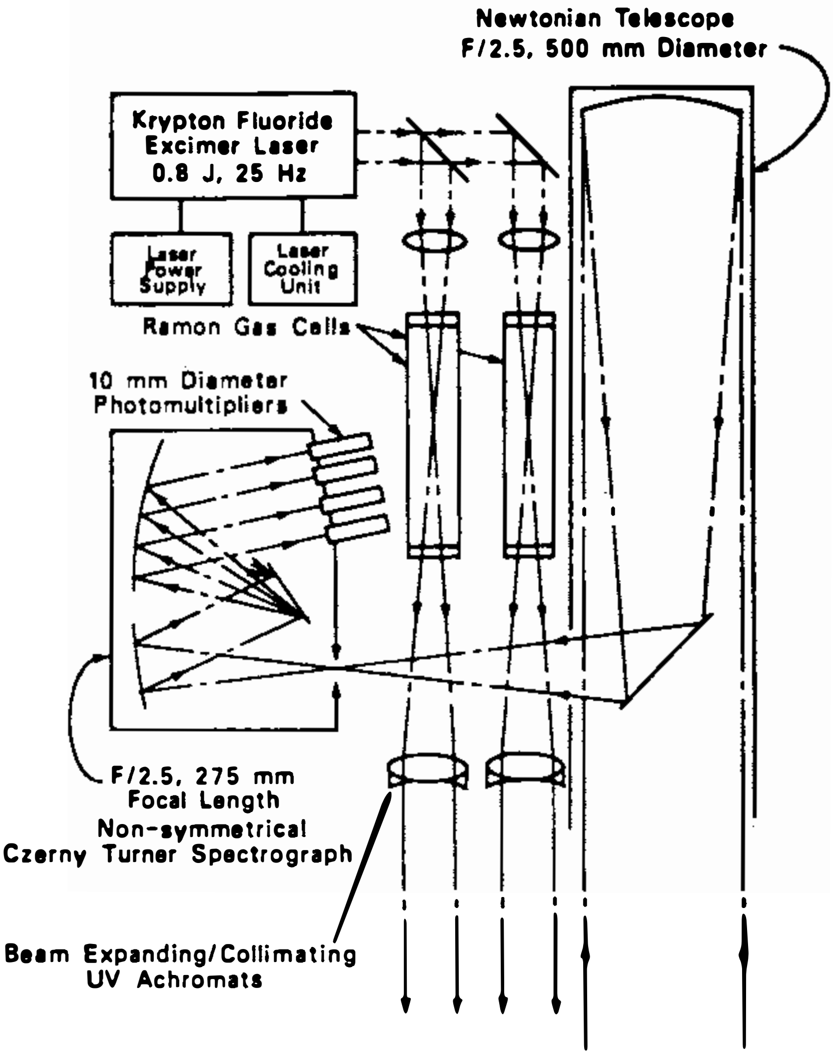

FIGURE 4 UV DIAL concept.

hazardous pollutants following an accidental release into the atmosphere. The SF_e concentration profile for a single pulse-pair from two tunable CO_2 lasers is shown in Figure 5, which also shows a contour map of the distributions of the tracer gas over a single transect. These results indicate that a range-resolved detection capability of 20 ppb is possible with this technique.

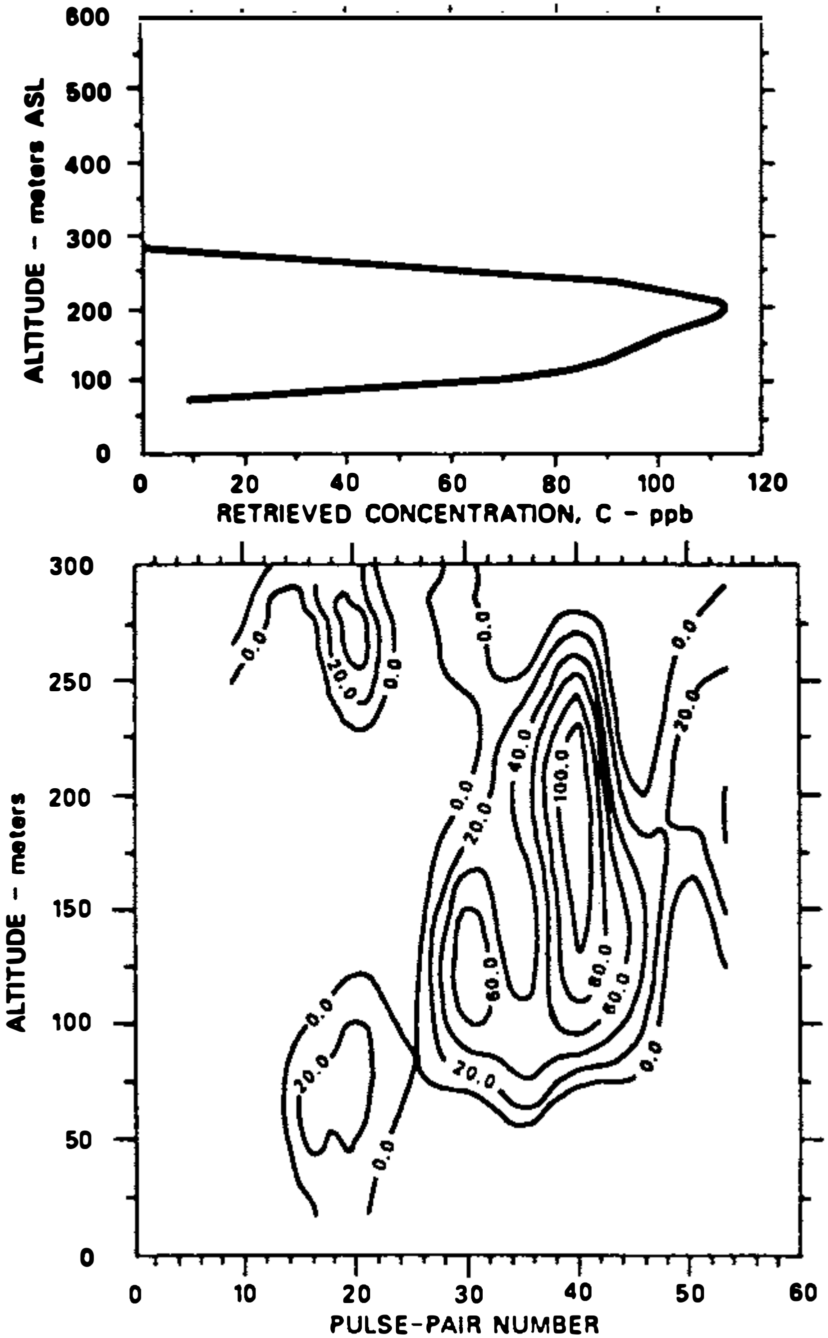

FIGURE 5 Contour map of vertical SF_6 distributions in ppb.

LASER FLUOROSENSOR SYSTEMS

The last of the three classes of systems to be discussed is the laser fluorosensor. Initially, airborne laser fluorosensing systems were developed to locate and identify the source of petrochemicals in lakes and river systems. Subsequently, development efforts were directed toward a number of other water quality parameters. Operational airborne systems are used by a number of research centers, including EPA's Environmental Monitoring Systems Laboratory in Las Vegas, Nevada; the Canadian Center for Remote Sensing; the University of Oldenburg (FRG); and the NASA facility at Wallops Island, Virginia. Applications for laser fluorosensors include:

- Optical attenuation coefficient measurements;
- Observations of the mixing and interfacing of marine and fresh waters;
- Locating, mapping, and fingerprinting petrochemical spills and discharges;
- Assessing the relative contribution of point and non-point source pollution to receiving waters;
- Flow, dispersion, and mixing studies using fluorescent dyes;
- Bathymetry;
- Column or range-resolved concentration measurements of algal pigments;
- Estimating acidification parameters in surface waters, e.g., pH, [Al], [DOC], [HCO_3], [SO_4].

Existing systems are capable of mapping changes in concentrations of chlorophyll *a* and dissolved organic carbon (DOC). The chlorophyll *a* concentration is an indicator of phytoplankton (planktonic algae) activity, and high levels result from high nutrient levels introduced via sewage effluents and agricultural runoff. The concentration of DOC in surface waters indicates the carbon equivalent of natural and anthropogenic dissolved organic materials which are present.

A typical fluorescence emission spectrum for the measurement of these two water quality parameters, which also permits an estimate of the optical attenuation coefficient for the water column, is shown in Figure 6. It is generally accepted that a broad fluorescence band resulting from excitation at 475 nm, which peaks at about 540 nm, is due to dissolved organic matter (DOM) in the

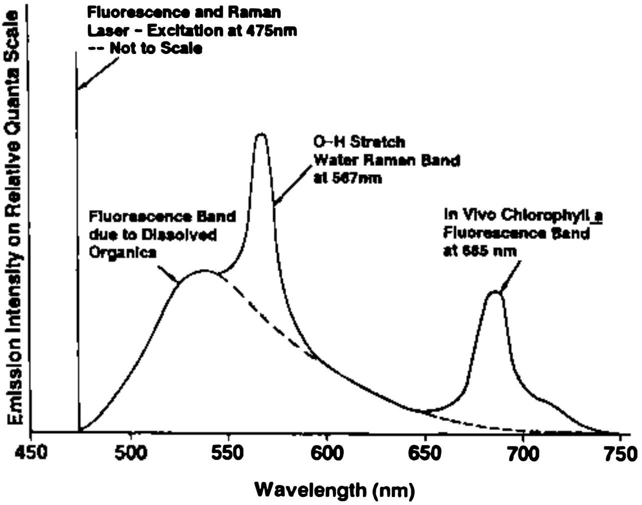

FIGURE 6 Typical fluorescence emission spectrum.

water. A universal relationship has not been established between DOM and DOC, as DOM fluorescence at a given wavelength is a function of such factors as pH, temperature, concentration of heavy metal ions, and constituency of natural and anthropogenic DOM. However, if a high degree of correlation can be established for a given water body between DOM fluoresence and measured DOC concentrations, then DOM can be used as a valid indicator of DOC (Bristow et al. 1985).

Also observable in the spectrum is the fluorescence band due to the presence of chlorophyll *a* and a Raman emission band from the OH vibrational stretching mode of water. As the latter peak is only weakly dependent on salinity and temperature, it can be an effective indicator of changes in optical attenuation, particularly in fresh water measured at a fixed wavelength (Bristow et al. 1981).

The use of an airborne laser fluorosensing system to measure chlorophyll *a* and the optical attenuation coefficient was demonstrated in a study conducted by EPA and the University of Nevada, Las Vegas, in Lake Meade, Nevada (Bristow et al. 1981). A schematic of the system used in the study is shown in Figure 7. Ground truth information (*in situ* fluorometry for chlorophyll *a* concentration and transmissometry for optical transmittance) was collected at 14 marker buoys in the lake.

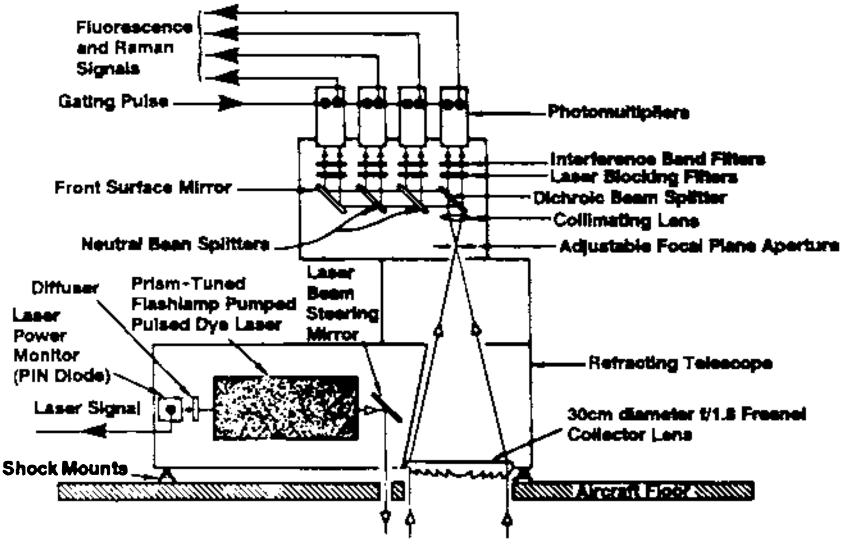

FIGURE 7 **Laser fluorosensor concept.**

The profiles for chlorophyll *a* fluorescence (P_F) and the water Raman (P_R) signals obtained during the overflight are shown in Figure 8. When the data are normalized for depth of penetration, a comparison of the (P_F/P_R) trace with ground truth measurements of chlorophyll *a* from the 28 grab samples shows a high degree of correlation between those two parameters over the flight path.

Another demonstration of this system was conducted along the Columbia and Snake rivers and included correlations of DOC in addition to chlorophyll *a* and the optical attenuation coefficient. In addition to the demonstrated ability of the laser fluorosensor to measure several parameters simultaneously, this study showed that the interrelationships between the various parameters measured were of greater significance than the measurements of the parameters themselves in removing ambiguities and providing insight into otherwise anomalous data (Bristow et al. 1985). The airborne laser fluorosensor data generally exhibit a simple linear relationship with measured water quality parameters. The system was also able to measure chlorophyll *a* and DOC in highly turbid and generally inaccessible freshwater reaches of the rivers.

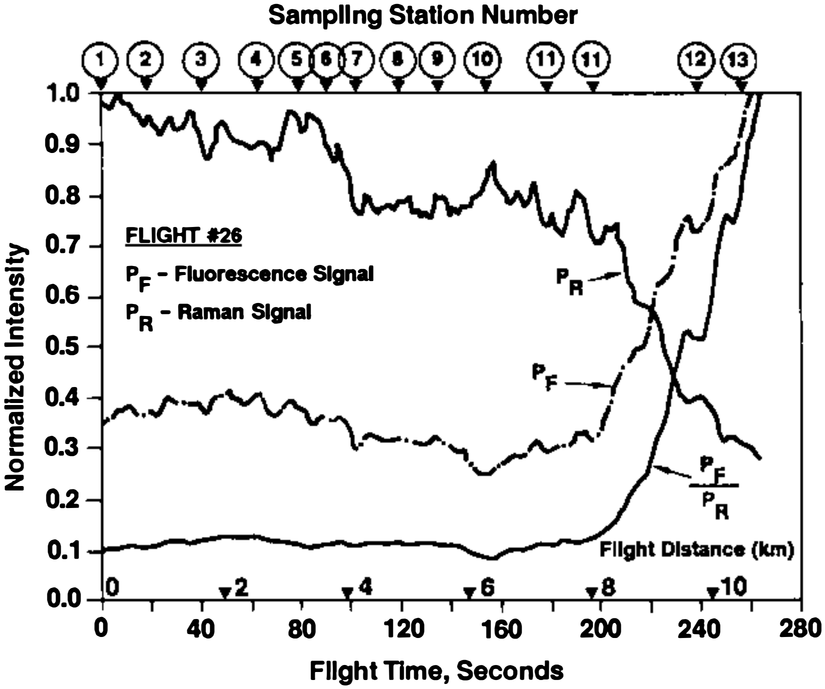

FIGURE 8 Fluorescence and Raman profiles for the Las Vegas wash.

Current interest in laser fluorosensing is directed at elucidating the relationship which has been demonstrated between DOM fluorescence and the parameters related to acid deposition. EPA is developing and testing a second generation airborne laser fluorosensor system designed to quantify lake water pH, DOC, and aluminum concentrations.

Laboratory fluorescence studies using multiple regression analyses have demonstrated relationships between DOM fluorescence properties and pH, DOC, and aluminum concentrations (Vertucci and Vodacek 1985). Raman normalized fluorescence spectra and limnological data were obtained from water samples from 49 Adirondack lakes for this program. Measurements included pH, alkalinity, total reactive aluminum, and DOC. Fluorescence intensity generally increased with DOC while the peak shifted to shorter wavelengths for high aluminum and low pH samples. The correlation between the normalized Raman fluoresence and DOC was significant at all wavelengths, although a wavelength dependency was observed. Significant correlations were also established between the fluorescence spectra and pH and between pH and the wavelength at maximum peak height and skewness of the spectra.

A multiple linear regression analysis of these data used a multivariate model based on fluorescence at specific wavelengths and the skewness and kurtosis of the spectra to predict sample pH. The R^2 for the regression of this data was 0.83. The relationships involving DOC and aluminum concentrations which are somewhat pH dependent were considerably weaker, although their prediction was improved when the pH of the samples was taken into account.

Currently, EPA's laser fluorosensor is being modified to measure DOM fluorescence with higher spectral resolution, which should provide more precise measurements of acid deposition parameters, pH, DOC, and aluminum concentration. Future efforts will include attempts to correlate DOC fluorescence with other lake water parameters, including sulfate and bicarbonate—for which the chemistry is well understood—as well as nitrate and nitrite ions. If significant correlations result, consideration will be given to developing a laser-Raman system in order to measure these parameters directly. Although the signal to noise ratio would be expected to be high, considerable success in stripping the broad spectrum fluorescence background has been achieved in Raman scattering experiments over the past several years.

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A Large-Scale Observation, Assessment, and Forecasting System For Heavy Metal Atmospheric Transport

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The State Environmental Pollution Observation and Monitoring Service, a national environmental pollution monitoring system, has been established and is operating successfully in the USSR (7,8). It draws from organizations of the USSR State Committee for Hydrometeorology and Control of the Natural Environment, with the participation of institutes of the Academy of Sciences of the USSR and other ministries and departments.

The underlying philosophy of comprehensive investigations which is the basis for this service provides for a systematic, integrated approach to monitoring, with concurrent monitoring of pollutant levels in the environment and hydrometeorological and biological observations. This approach yields more information, is more efficient, and at the same time is more cost-effective to operate. Furthermore—and this is extremely important—such an approach offers the opportunity in practical terms to establish an ecological service in the USSR on the basis of an existing pollution observation and monitoring service (7). The creation of this ecological service will provide scientifically validated assessments of the ecological consequences of anthropogenic impacts, and it will be used to formulate practical recommendations for ecologically acceptable standards in order to regulate these impacts.

One of the most significant negative repercussions of man's activity is his discharge of contaminants into the environment. The generation of accurate data on pollutant levels in different components of the environment is a problem that is under intense scrutiny through large-scale monitoring systems which have recently been established. These include activities of the United Nations Environmental Program (UNEP) as well as activities pursuant to the Agreement on Cooperation between Comecon Member States in the Area of Environmental Protection (2,13). Heavy metals and, more specifically, their release into the atmosphere are a top priority in the establishment, development, and practical implementation of all large-scale, global and regional monitoring systems of this kind (7).

It has previously been established from examples of global mercury circulation that there is considerable inertia in mercury redistribution between media. After discharge into the atmosphere is discontinued, mercury levels in surface waters as a whole will continue to increase for tens and even hundreds of years. Investigation of the system which describes mercury regional-scale circulation indicates that the hydrosphere is the limiting medium. Calculations have demonstrated that in many practical instances, ambient mercury levels in the atmosphere must be 10 or even 100 times lower than the maximum permissible health standards in order to ensure that the concentrations do not exceed maximum permissible levels in water.

This example illustrates the need for an approach based on a comprehensive analysis of the negative consequences associated with heavy metal discharges into the atmosphere. We shall describe below an experiment designed to develop, scientifically validate, and implement large-scale systems for monitoring ambient levels of heavy metals. This kind of monitoring is seen as a well-balanced, flexible system of observation, evaluation, and generalization. Predictions are then formulated based on the findings (7).

REGIONAL SCALE MONITORING: LAKE BAIKAL BASIN

As previous Soviet-American symposia have devoted much attention to Lake Baikal, a brief overview of the main points regarding this area is presented below (9,10). Our discussion will then turn to atmospheric pollutant transport, one of the critical aspects of a comprehensive monitoring system.

The aim of this kind of monitoring program is to evaluate, predict, and prevent the negative consequences of anthropogenic alterations in the status of Lake Baikal and the adjacent environment. The development of such a system coincided with the opening of the Baikal Pulp and Paper Plant (BPPP) in 1966. This is the only major plant built directly on the lake's shore.

The program's primary goals were to measure and monitor amounts of pollutant input into the lake from BPPP discharges and to assess the zones of impact on the lake, as a certain amount of pollution was released into the lake despite the plant's highly effective—and costly—waste treatment facilities. These goals were met (10).

At the same time, it became clear that in assessing the anthropogenic impact on the lake it was not enough—and was impossible in practical terms—to limit ourselves to the problem of BPPP wastes alone. We needed to address the entire range of anthropogenic impacts related to the development of economic activity in the adjacent areas of Eastern Siberia: the increase in the area's population; the growth of energy needs, industry, and transportation; and heightened recreational activities. Many of these factors are associated with contaminant inputs (including toxic heavy metals) into the atmosphere and their subsequent deposition on the lake's waters and the region's watershed. Such a situation may induce negative consequences.

Published data on the findings of experimental research on meteorological processes and the status of atmospheric characteristics (i.e., determining the dynamics of contaminant behavior and the physical and chemical transformations) leaves many gray areas still to be resolved. We therefore planned and carried out comprehensive investigations of the conditions regarding contaminant transport and fallout from the atmosphere in the Lake Baikal region.

Lake Baikal is situated in the heart of the Asian continent between approximately 51° and 56° north latitude, the latitudes of Kiev and Moscow. It is quite remote from any oceans, lying in a narrow tectonic depression known as the Baikal Trench which exhibits a prevailing northeast tilt. Baikal's length in this direction is 836 kilometers, with a maximum width of about 80 kilometers. The lake covers 31,500 square kilometers, while the Baikal Trench occupies more than 80,000 square kilometers if its boundaries are followed along the watershed line which borders its ranges. These ranges reach a height of 2,300 meters in the southern portion of the depression, 1,000–1,700 meters in the southwest, and 2,500–2,800 meters in the north, northwest, and northeast in the Baikal and Barguzin ranges. Individual peaks exceed these heights.

The median height of the mountainous areas above the level of Lake Baikal varies between 800 meters in the south and 2,000 meters and more along the northwestern, northeastern, and northern portions of its periphery. Broad expanses along the edges of the Baikal depression are confined to the area in which the source of the Angara River is located, to the outlet of the spacious Tunkin Trough, and to the mouths of the Selenga, Barguzin, Upper Angara, and Kichera Rivers. These areas substantially influence the lake's seasonal metereological processes, facilitating the intrusion into the Baikal depression of air masses from continental regions. Such intrusions are particularly evident in diurnal cold season weather processes before the lake freezes over.

Intrusion processes such as mountain-pass winds (largely through the western ranges in the cold season of the year) are stable until the lake freezes. They may approximate a winter monsoon in the form of a so-called "monsoon trend," but they may also occur in other seasons when atmospheric fronts pass through the Baikal region. Due to the convergence of air currents entering the Baikal Trench, local high wind centers are formed in the open reaches and valleys bordering the lake. Wind currents are not only intensified considerably (with speeds up to tens of kilometers per second), but they are also oriented in a specific direction. They act as an impulse in the formation and dynamics of intra-basin circulation which we traced in our *in situ* investigations. Various kinds of particulate clearly enter into such circulation. This particulate is transported over the Baikal region with macro-advection and localizes over the shoreline as well as over the lake itself (21).

We have formulated a picture of the climate and air currents in the Lake Baikal region as an open dynamic system with direct and inverse relationships with the surrounding land mass. It is

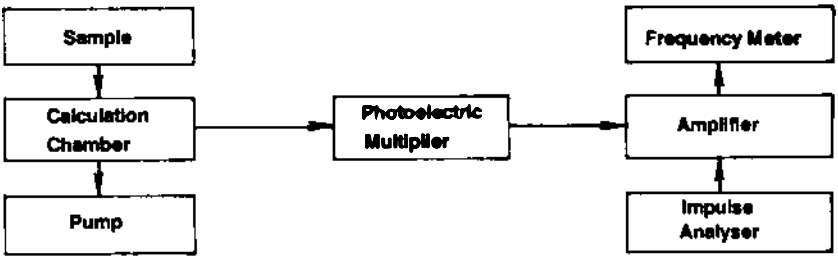

FIGURE 1 Schematic representation of laser aerosol dispersion analyser.

also subjected to the impact of a tremendous body of water. As a result, monitoring must encompass the entire lake basin and a considerable portion of the adjacent areas. Climate fluctuations in these territorial extremes and deterioriated atmospheric conditions can affect water quality in the Baikal tributaries through precipation, runoff, and atmospheric dynamics which associate the lake with land.

Aerosol samples have been taken annually since 1974 over a reference cross section with subsequent determinations made of heavy metal levels. In recent years we have used a photoelectric laser aerosol dispersion analyzer whose schematic representation is shown in Figure 1.

Aerosol-containing air in the analyzer is pumped through the darkened cylindrical channel. Aerosol particles, entrained by the air current, enter the calculation chamber and intersect light rays formed by diaphragms and optical elements. A light impulse originating from a particle bears information about its size. The light signal is converted into an electrical one and enters the amplitude analyzer. From the analyzer, the size is assigned a channel number (the number of impulses in the channel corresponds to the number of particles of a given dimension), and the information is read out on a screen and a digital printer. Given the instrument's dynamic range, we can record aerosols at intervals from 0.1 to 80 um.

With favorable weather conditions and precluding impact from anthropogenic aerosol release points and attenuated input from natural sources, we recorded extremely low aerosol levels (to 13 particles per cm^3) with particle size less than 0.8 um. This corresponds to the aerosol mass level of 2×10^{-7} mg/l. The median aerosol level at distances from the shoreline of under five kilometers amounts to 210 particles/cm^3 or 3×10^{-6} mg/l.

Table 1

Concentrations of elements in ambient air over Lake Baikal (ng/m^3) and in the region's snowmelt runoff (mcg/l)

Element	Atmosphere	Snow	Pristine background regions (atmosphere)
As	0.072 - 0.32	--	0.02 - 15
Br	0.05 - 0.7	--	0.17 - 120
Ca	170.00 - 890	700	--
Co	0.04 - 0.35	--	0.004 - 3
Cr	2.2 - 5.6	--	0.6 - 37
Cu	2.0 - 160	1.1	0.5 - 90
Fe	27.0 - 320	15	9.0 - 1000
Hg	0.025	0.28	0.02 - 32
Li	--	0.19	--
Na	35.0 - 780	180	10.0 - 1000
Pb	--	1.0	--
Sb	0.02 - 0.27	--	0.02 - 10
Se	0.012 - 0.2	--	0.008 - 1.5
Zn	2.4 - 8.8	17	2.0 - 70

Source: (11)

Table 1 cites data on the levels of a range of metals in ambient aerosol and snowmelt runoff. It is clear from this data that the air over the lake's water area is only slightly subjected to anthropogenic impact. Therefore, for these indices the Lake Baikal region is one of the world's pristine background regions.

ASSESSMENT OF ANTHROPOGENIC IMPACT ON HEAVY METAL BALANCE IN THE ATMOSPHERE: THE MERCURY EXAMPLE

Fuel energy, ferrous and nonferrous metallurgy, mobile sources, and urban waste combustion are major anthropogenic sources of heavy metal input into the atmosphere. Coal heads the list of fossil fuels in terms of production and utilization. Large masses of various trace elements (frequently in excess of amounts used in industry) are released into the environment from overburden rock, enrichment wastes, ash, and slag from coal extraction and utilization (1).

Many trace elements are toxic to varying degrees. We know from geochemical ecology that it is not desirable to discharge excessive amounts of such elements as mercury, beryllium, arsenic, cadmium, lead, zinc, vanadium, copper, chrome, and certain others into the organic matter of the biosphere. We have previously discussed the potential negative repercussions of mercury and lead accumulation in the biosphere (4-6). Many heavy metals which are observed in ambient air act as a catalyst for oxidation reactions occurring in the atmosphere (17). This may hold tremendous, truly global significance for atmospheric chemistry and, in particular, for oxidation processes in the environment. Furthermore, investigations indicate that such reactions with the participation of heavy metals are important sources of free radicals in ambient air (18). It is difficult to overestimate the ecological and medical significance of this fact.

Accurate methods for evaluating anthropogenic impact on the heavy metal balance in the atmosphere are necessary to assess these phenomena. We shall examine these issues using mercury as an example. Anthropogenic mercury input into the environment (e.g., atmosphere, natural waters, soils) currently amounts to approximately one-third of total input from both anthropogenic and natural sources (5,15). Natural fluxes include so-called "mercury respiration" of the earth's crust and vegetation which involves mercury evaporation into the atmosphere (92 percent) and mercury input into natural waters during natural denudation of land surface rock (8 percent). Approximately two-thirds of the anthropogenic input enters soils. About four percent finds its way to water and no more than one-third enters the atmosphere.

Let us focus on the following:

- Published data on mercury levels in components of the environment are inconsistent. This makes it much more difficult to compile a complete balance structure for mercury fluxes (3,16).
- The anthropogenic contribution to mercury release into the atmosphere totals approximately 15 percent.
- The poorly studied processes of "mercury respiration" of the earth's crust and vegetation play a predominant role in natural mercury input.
- Combustion of coal and other kinds of fossil fuels currently

accounts for approximately three percent of total mercury input into the atmosphere.

In relation to the last factor, not only must fuel combustion processes be considered in assessing the contribution of combustible fuel energy to mercury input, but the entire range of energy production and consumption processes must also be assessed. The interdisciplinary balance developed by the American economist Wassily Leontief is a convenient tool for this purpose. The application of this method shows a significant increase (1.5–2.0 times) in the role of thermal electric power stations in the current and predicted structure of anthropogenic release points. Contemporary energy systems of individual countries and the energy system of the world at large are in a transitional stage (16). A goal has been set to tap richer energy sources which are acceptable in both socioeconomic and ecological terms. However, one can expect an increase in the coming decades in the magnitude of exploration, production, and use of traditional power resources—coal, oil and petroleum products—in addition to the expansion of atomic energy use and despite a downturn in the energy intensiveness of different branches of the economy.

"Reservoir" models based on the use of first order kinetics are widely used in quantifying anthropogenic impacts on the global mercury balance (4,19). Studies 4, 5, 7, and 12 detail mercury input into the atmosphere, using a mathematical model whose matrix notation can be presented as follows (19):

$$\frac{dQ}{dt} = AQ + I \qquad \{1\}$$

where $Q = Qi$ is the mercury content vector in components (reservoirs) of the environment; Qi is the mercury level in an "i-th" reservoir; $I = Ii$ is the vector for mercury input into the environment; Ii is the mercury release into an "i-th" reservoir; and A is the matrix of mercury inter-reservoir transport rates.

It usually takes several years for major sources of mercury input into the environment to alter output. This considerably exceeds both global air mass exchange time (less than one year) and mercury residence time in the atmosphere (approximately ten days). Consequently, we can postulate that dQ/dt in formula 1 is equal to zero, from which it follows that:

Table 2

Function of single mercury source impact (one ton per year) on mercury fluxes from the atmosphere

Block Receptor	Block Source 70° - 30°	30° - 0°	0° - 30°	30° - 70°
90° - 70°	0.021	2.3×10^{-3}	2.4×10^{-4}	4.9×10^{-5}
70° - 30°	$\frac{0.805}{0.28}$	$\frac{0.072}{0.033}$	$\frac{7.3 \times 10^{-3}}{3.3 \times 10^{-3}}$	$\frac{1.5 \times 10^{-3}}{0.69 \times 10^{-3}}$
30° - 0°	$\frac{0.16}{0.11}$	$\frac{0.874}{0.36}$	$\frac{0.055}{0.039}$	$\frac{0.011}{7.8 \times 10^{-3}}$
0° - 30°	$\frac{0.013}{9.8 \times 10^{-3}}$	$\frac{0.043}{0.033}$	$\frac{0.823}{0.41}$	$\frac{0.116}{0.90}$
30° - 70°	$\frac{2.5 \times 10^{-3}}{2.3 \times 10^{-3}}$	$\frac{8.5 \times 10^{-3}}{8.0 \times 10^{-3}}$	$\frac{0.112}{0.1}$	$\frac{0.855}{0.61}$
70° - 90°	6.0×10^{-5}	2.1×10^{-4}	2.7×10^{-3}	0.016

Note: For the figures a/b in the table: a = flux (t) on entire underlying surface in the block; b = flux (t) on ocean surface in the block.

Source: (14)

$$Q = -A^{-1} I \qquad \{2\}$$

We used findings from observations of mercury levels in components of the Lake Baikal basin environment to verify this model. We found in particular that mercury concentrations on the order of 0.2–0.4 ug/l should be formed due to global atmospheric mercury transport over a geologically significant period of the lake's evolution. This is in close agreement with observed data (4).

Table 2 cites the findings from calculations with a reservoir model for global mercury transport in the troposphere. It shows values for the function of the impact of each block on mercury fluxes from the atmosphere to an underlying surface (including the ocean) per individual (one ton per year) mercury release point (14). Results of these calculations can be used to evaluate current and predicted mercury fluxes from the atmosphere to various regions of the planet. Calculation findings for the period up to 2015 indicate that both mercury input into the atmosphere and fluxes from the atmosphere to underlying surfaces will increase by 25–35 percent.

In contrast to mercury, anthropogenic input of lead into waters of the world's oceans is already significant and will be even more so in the future (3,6). This circumstance calls for in-depth analysis in order to evaluate potential negative ecological repercussions. However, serious concomitant ecological problems are also linked with mercury both currently and in the future, when industrial waste treatment facilities for mercury will be further upgraded and the atmosphere becomes the primary pathway of mercury input into the environment. Mercury's high volatility enhances its diffusion over great distances. The result is that aquatic ecosystems become the critical, limiting link. In particular, Soviet researchers have demonstrated the validity of this conclusion with regard to shallow water bodies with a large watershed (4,7,12). Furthermore, because of the dependency of volatility on temperature, mercury will accumulate in cold components of the environment, particularly in cold waters of the world's oceans.

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US-USSR Bering Sea Study

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The 1972 bilateral agreement on US-USSR cooperation in environmental protection (Project 02.05-41 "Biosphere Reserves;" subtheme: Bering Sea Ecosystem Studies) resulted in a joint expedition in the Bering Sea from June 27–July 31, 1984, on the Soviet research vessel *Akademik Korolev*. This second joint US-USSR expedition followed a previous joint investigation in the Eastern Bering Sea in 1977. The principal sponsoring agencies were the Soviet National Environment and Climate Monitoring Laboratory, the Academy of Sciences of the USSR, and the US Fish and Wildlife Service of the US Department of Interior. Scientific personnel came from a variety of institutions in both countries.

The principal objectives of the study were to determine any unnatural changes in the structure and functioning of the Bering Sea ecosystem and to assess its assimilative capacity. More specifically, the main scientific goals were to collect biological, chemical, and physical baseline data to provide a comprehensive profile of the Bering Sea; to conduct studies of the physiological and ecological characteristics of plankton organisms; and to assess the relative ecological health of the Bering Sea.

Sixteen American scientists joined the Soviet ship at Dutch Harbor, Alaska, to collect samples on a series of four polygon sampling sites (five stations in the form of a box) located in the southern, eastern, northern, and western regions of the Bering Sea. A few additional stations were added to the northern polygon to improve sampling of reportedly high primary production and

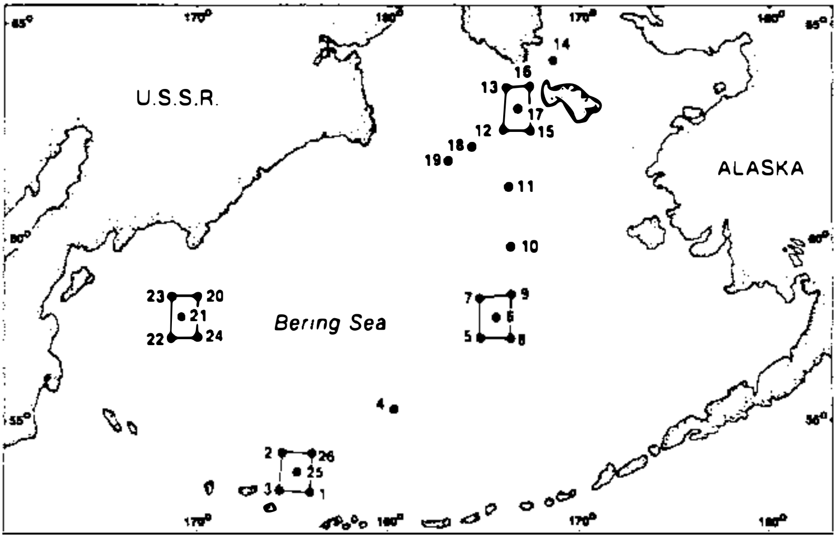

FIGURE 1 Sampling locations during the joint US-USSR Bering Sea Study. Polygon locations (five station clusters) were sampled in the southern, eastern, northern, and western regions from June 27 - July 31, 1984.

degradation in that region. Six working groups were established to encourage interactions between Soviet and American scientists in physical oceanography; biogenic elements; biogeochemical cycles; microbiology; plankton and primary production; and zoobenthos, birds, and marine mammals. These groups also designed the sampling protocols for the 26 stations, whose locations are shown in Figure 1.

MEASUREMENTS BY US PARTICIPANTS

As previously mentioned, specialists from both countries were merged in the working groups to facilitate a comprehensive investigation of the Bering Sea. Overall, the activities of the US specialists complemented the research performed by their Soviet colleagues. The following American projects and measurements were undertaken at the sampling stations:

1. Expendable bathythermograph measurements of water temperature in the upper 200 meters;
2. Salinity-temperature-depth profiles in the upper 400 meters;
3. Concentration of dissolved inorganic plant nutrients in all hydrographic samples from the surface to 4,000 meters;
4. Concentration of dissolved oxygen (conducted jointly with USSR);
5. Concentration of heavy metals in samples obtained with a Kevlar sampling line;
6. Dissolved and suspended organic carbon, especially in the euphotic zone;
7. Concentrations of C_1 - C_4 and C_5 - C_{15} hydrocarbons in water samples;
8. Concentrations of C_{14} - C_{32} hydrocarbons in benthic sediments;
9. Rates of primary production using ^{14}C isotopes (conducted jointly with USSR);
10. Concentration of chlorophyll *a* using *in vitro* fluorescence;
11. Concentration of phytoplankton pigments (chlorophyll *a*, chlorophyll *b*, phaeophorbide, fucoxanthin and peridinin) using high pressure liquid chromatography;
12. Vertical distribution of ambient light to calculate extinction coefficients;
13. Taxonomic composition and quantitative assessment of benthic organisms (conducted jointly with USSR);
14. Granular analysis of sediment samples (conducted jointly with USSR);
15. Taxonomic composition, quantitative assessment, and feeding habits of sea birds;
16. Quantitative assessment of marine mammals.

COLLABORATIVE US-USSR EXPERIMENTS

Some of the most interesting and potentially useful results were obtained in several collaborative experiments to study effects which could not be generated in individual experiments. This approach was used to evaluate the simultaneous effects of varying nutrient and toxicant concentrations (Cd, Cu, Pb) on planktonic communities. It was interesting to learn that high concentrations of nitrate decreased the toxic effect of copper on microzooplankton in seawater. Further experiments were designed to explore the effects of both phosphate and nitrate on succession of species in the oceanic environment in order to better understand the biological processes occurring at frontal regions between different water masses. Another interesting collaborative experiment was designed to study the effect of nutrient regimes on the intensity of PCB bacterial degradation in the relatively frigid climate of the Bering Sea.

Eight collaborative experiments were carried out during the 36-day cruise. The data from these experiments have not been completely analyzed to date, but a joint meeting to complete a synthesis of the data sets is anticipated.

Scientific personnel of the joint US-USSR Bering Sea expedition were brought together for two scientific meetings. The first meeting consisted of four presentations on the theme "Ecological Problems of Study and Monitoring of Highly Productive World Ocean Areas." A second meeting consisted of six presentations on the theme "Current State of Knowledge about the Bering Sea Ecosystem."

SUMMARY OF FINDINGS

The Bering Sea is a large body of water with a unique characteristic: 44 percent of the area is comprised of continental shelf. This large shelf area produces a suitable habitat for large quantities of plant and animal life. The natural variability in such a large ecosystem prevents a thorough analysis with only a single expedition. However, some general findings of the expedition follow.

- As many as four water masses were observed in the vertical sampling of physical oceanographic parameters. Vertical nutrient distributions indicated three water masses (surface, intermediate, and deep water) in the southern and western polygon.
- Horizontal sampling identified three water masses (Coastal, Bering Shelf, and Anadyr) which have quite different chemical features and origins.

- The plankton community produces a decisive influence on nutrient concentrations in the euphotic zone and provides abundant material for a high intensity of microbial degradation.
- Copper complexing capacity of seawater samples declined with depth in direct relation to the decline of phytoplankton biomasses as indicated by chlorophyll *a* concentrations.
- The Bering Sea ecosystem is a highly productive ecosystem, and at present anthropogenic impact does not produce a significant effect on bioproductive processes in the Bering Sea.

A joint US-USSR compendium containing the final analysis of the research expedition will be published with the tentative title "Investigations of the Bering Sea Ecosystem: Part II." Exchange of data has occurred, and a synthesis workshop will be arranged to continue the process of data analysis and publication of complete results. There was also general agreement among the study participants that a third US-USSR expedition should be planned for the Pacific Ocean, including the Bering Sea and highly productive coral reef ecosystems.

ACKNOWLEDGEMENT

Contribution No. 87-004 of the Marine Science Institute, University of Texas, Austin. Partial support for this research was provided by NSF Grant No. DPP8300916, the US Fish and Wildlife Service, the US Department of Interior, and the US Environmental Protection Agency.

Comprehensive Analysis of the Bering Sea Ecosystem

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The emergence of new and powerful, man-induced, ecological factors capable of affecting the evolution of marine ecosystems has stimulated in-depth, baseline studies of the world's oceans. Interest in these factors has given rise to new scientific disciplines, such as the anthropogenic ecology of the ocean—a new and rapidly expanding area of modern oceanography (8).

A starting point for anthropogenic ecology of the ocean lies in ideas and methods developed within the framework of scientific investigations into the negative consequences of anthropogenic impacts on the ocean. The focus of these studies is the tracing of global changes in the ecological characteristics of the marine environment which have relevance to the ecological evaluation of the state of the biosphere at large. Underlying such studies is a comprehensive analysis of the status of marine ecosystems in terms of geographic zonality and the extent of anthropogenic impact.

Comprehensive studies of the Bering Sea's ecosystem have contributed substantially to developing the field of anthropogenic ocean ecology. They were carried out both as part of national programs of scientific investigations and during joint Soviet-American research expeditions.

Any consideration of a comprehensive analysis of the Bering

Sea ecosystem must stress the benefits from both good organization and good programs at the international level. Experience from baseline studies and from the experimental phase of the comprehensive monitoring of several semi-enclosed seas (i.e., the Baltic and Mediterranean) demonstrates the need for scientists from different countries to develop a unified approach and standard methods for assessing the state of marine ecosystems. This kind of experience is gained during international expeditions, intercalibrations, and symposia.

The Bering Sea washes the shores of both the USSR and the United States. It is therefore only natural for Soviet and American scientists to pool their efforts to investigate the tolerance for and "immunity" of Bering Sea ecosystems to man-made pollutants. The need to evaluate the Bering Sea's assimilative capacity with a view to developing a regulatory system to control anthropogenic discharges stems from the predicted persistence of existing pollution trends for this region of the Pacific Ocean. (7)

The first joint Soviet-American expedition in the Bering Sea, which took place in 1977 on board the Soviet vessel *Volna*, set the stage for long-term comprehensive studies of the Bering Sea. The project's primary findings were compiled in a joint monograph entitled "Ecosystem Investigation of the Bering Sea," published both in the USSR (6) and the USA (26).

Ecosystem investigations of the Bering Sea were subsequently extended during the comprehensive ecological expedition in the northern Pacific Ocean. Soviet specialists conducted these studies from June through August 1981 on board the Soviet ship *Akademik Shirshov.* This voyage yielded new scientific material describing the status of the Bering Sea ecosystem: hydrological processes and hydrochemical conditions; the impact of pollutants on the plankton community in microcosm conditions; microbial oxidation of organic toxicants; the spatial structure of plankton biological activity; and the Bering Sea's biotic balance. Ground-breaking studies were conducted on the composition and physiological activity of the Bering Sea's bacterial population. Benz(a)pyrene in the marine ecosystem was used to study the biogeochemical cycle of polycyclic aromatic hydrocarbons. The expedition's findings were published in the monograph "Comprehensive Analysis of the Bering Sea Ecosytem."

The second Soviet-American expedition in the Bering Sea took place in June 1984 on the Soviet ship *Akademik Korolev.* The

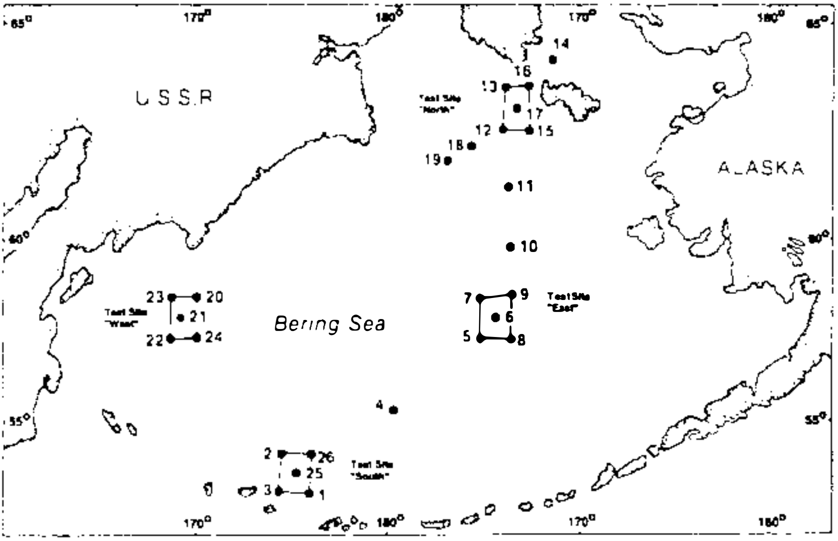

FIGURE 1 Location of stations for the second Soviet-American expedition in the Bering Sea, Summer 1984.

project focused on studying processes occurring within clearly defined test sites and cross sections joining different test sites (Figure 1). The investigations in both 1981 and 1984 were conducted in the same areas of the Bering Sea (24). The regions where the test sites were situated exhibited a number of specific features, but had differing water mass qualities.

Test site 1 ("South") was located in the deep-water, southern area of the Aleutian Trench. Test site 2 ("East") was located on the border of the eastern continental slope. Both of these areas are subjected to the impact of Pacific Ocean waters which penetrate the Bering Sea across the Aleutian Ridge, intersecting the sea's central portion from the southeast to the northwest with a system of transverse currents. Test site 3 ("North") covered the area of the continental shelf west of St. Lawrence Island with a depth of between 50 and 100 meters. This is the zone which is subjected to the impact of cold water masses and whose basic nucleus is preserved throughout the entire summer period. Test site 4 ("West") was located within the deepwater western Bering Sea over the submerged Shirshov chain; the cold Kamchatka Current flows into this area. In addition, cross section No. 1 joined test sites "South" and "East," cross section No. 2 united "East" and "North," and cross section No. 3 linked "North" to "West."

A comprehensive analysis of Bering Sea ecosystems touches upon a broad range of issues. This monograph presents and invites discussion of specific results of the second Soviet American expedition including: (1) features of hydrological and hydrochemical processes; (2) quantification of pelagic populations and elements of the biotic balance; (3) microflora and microbiological processes; (4) biogeochemical cycles and organic pollutants; (5) ecological and toxicological investigations; and (6) approaches to determining the assimilative capacity of the Bering Sea.

FEATURES OF HYDROLOGICAL AND HYDROCHEMICAL PROCESSES

The Bering Sea is a unique basin in which highly contrasting conditions and processes converge. On the one hand, the Bering Sea is a semi-closed marine aquatic system. At the same time, it is a typical ocean ecosystem. The Bering Sea is located almost entirely within the subarctic climatic zone. Only its extreme northern and southern boundaries extend into the Arctic and temperate latitudinal zones, respectively.

Current oceanographic investigations of the Bering Sea have shown that the main sources of the region's water mass formation are in the Alaska Current which flows across the straits between the Aleutian and Komandorskiye Islands. A counterclockwise water mass cycle actively transports nutrients in the Bering Sea's main regions. The water mass in the basin's northern and eastern portions on the expansive continental shelf is cooled during the winter and retains its low temperatures throughout the entire summer. The cold current in the western portion flows near the Siberian and Kamchatka shorelines. River flows, metereological factors, and atmospheric circulation exert a significant influence on the formation of the Bering Sea's water masses, water structure, and hydrological conditions (6).

Four characteristic water masses were detected during the 1984 investigations with specific features of temperature and salinity distribution: surface, intermediate cold, intermediate warm, and deep-water masses. The cold intermediate layer is usually formed under the impact of climatic factors: winter cooling of the entire active layer and subsequent summer warming of its uppermost portion. Formation of the warm intermediate layer is coupled with the transformation of Pacific Ocean waters which are cooled by winter convection. The four-layer water mass structure was observed at all test sites investigated, with the exception of the "North" site.

The winter-summer warming in the area of water under study was not uniform. This affected the thickness of the surficial layer which increased from the northwest to the southeast. Characteristic cold and intermediate warm layers increased in thickness from the southeast to the northwest. At the same time, layer boundaries were observed only in the temperature field.

The powerful northern Pacific current flowing along the continental shelf in the northeastern portion of the basin determines one specific hydrochemical feature of the Bering Sea. The current rises to the surface, forming upwellings which saturate the euphotic zone with nutrients necessary for the vital activity of phytoplankton (24).

The Bering Sea's unique chemical features are futher underscored by the specific nature of molecular oxygen distribution in the water column. At a depth of approximately 1,000 meters the basin's water masses intrude, injecting these waters with a lethal oxygen deficit and high nutrient levels. This particular kind of "shallow water state" triggers a concentration and "entombment" of many organic elements introduced as a result of anthropogenic pollution of the Bering Sea. This factor must be taken into account in organizing a comprehensive monitoring program.

Nutrient dynamics in the euphotic zone usually reflect the specific features of the water body's hydrochemical conditions and are a function of the phytoplankton community's biological activity. Therefore, in bodies of water which exhibit a clearly defined seasonality—and the Bering Sea is a salient example—the annual nutrient cycle is an exact reflection of the annual plankton cycle. During the biological winter, which in the Bering Sea lasts from October to mid-May, nutrients saturate the trophogenic layer through intensive mixing of surface water with the intermediate cold mass. During the spring plankton bloom (mid-May to July) nutrient levels in the trophogenic layer drop to a minimum. These levels rise again in the summer period (July and August) due to organic matter destruction and nitrogen and phosphorus regeneration induced by the vital activity of bacterial plankton. Mineral components are injected into the surface layers from great depths during the spring vertical layer mixing. Therefore, another phytoplankton bloom frequently occurs in the autumn period.

During the 1984 investigations, nitrate levels decreased with the advent of the spring phytoplankton bloom. The rate of decrease for nutrient concentrations in the surficial layer was not uniform in the different water areas studied. Test site "South" exhibited nitrate levels in the surface layer of 15–20 ug of nitrogen per liter; the "East" site showed levels of 3–8 ug n/l. The amount of inorganic nitrogen compounds at the "North" and "West" sites fell to nearly analytical zero. A similar pattern was noted for dissolved phosphates, which at test site "South" fluctuated between 1.5 and 1.8 ug n/l, and at test site "East" from 0.9 to 1.0 ug n/l. Phosphorus compound levels did not exceed 0.5 ug n/l for the "North" and "West" sites. Nitrate and phosphate levels increased several times in the intermediate cold layer zone, peaking at this water mass' lower boundary (800–1,000 meters).

Silicon distribution is particularly interesting. Silicon is one of the most important nutrients, necessary to the vital functions of phytoplankton, particularly for diatomic algae. During the study, silicon levels were low for the entire water area, varying between 22 and 30 ug n/l at test sites "South" and "East," and not exceeding 1.5 ug n/l at the "North" and "West" test regions.

The greatest nutrient fluctuations were found in the surface water mass, which also exhibited a subsurface maximum oxygen concentration in the thermocline. Nutrient distribution for the intermediate and deep water masses, except for the shallow-water northern region, was fairly uniform.

The investigations demonstrated the specific hydrological and hydrochemical features of the Bering Sea which must be considered in studying biochemical cycles of chemical elements and compounds.

QUANTIFICATION OF THE PELAGIC POPULATION AND ELEMENTS OF THE BIOTIC BALANCE

The Bering Sea is one of the most productive areas of the world's oceans, yielding only to the regions of eastern Pacific and Atlantic upwellings (13,21,23,24,28,31). Despite the severe climate, primary production, and phytoplankton biomass in the Bering Sea reach high levels of more than 4 grams C/m^2 per day. Primary producers form the base of the Bering Sea food chain—phytoplankton and to a lesser extent attached algae (macrophytes).

During the integrated research voyages in the summers of 1981 and 1984, the seston mass in the Bering Sea averaged 66 g/m^2 per 0–45 meter layer. In June 1981 the minimum average values for the seston mass (44 g/m^2) were encountered in the "North" test site; maximum levels were recorded at the "East" site (98 g/m^2). In July 1984 the "North" site exhibited the highest values for seston mass (an average of 165 g/m^2); minima (30 g/m^2) were ascertained at the "West" test site (Table 1). Interannual fluctuations of mean seston mass levels for the "South," "East," and "West" test sites did not exceed two- to three-fold. This is apparent evidence of the stability of the biological processes in the areas of the Bering Sea under study for the years indicated.

Median phytoplankton biomass for all Bering Sea areas under study in 1981 and 1984 totaled 13–14 grams per square meter. Maximum values in the summer of 1981 for average phytoplankton biomass in the photosynthetic zone were found in the "West" site (22 g/m^2); the "South" site registered the lowest values (8 g/m^2). In 1984 the highest median levels of phytoplankton biomass were detected in the "North" site (21 g/m^2), with the "West" site exhibiting the lowest figures (9.5 g/m^2) (Table 1). The differences in the mean phytoplankton biomass at the different test sites for both 1981 and 1984 did not exceed threefold and were a function of different periods of plankton community succession.

The prevalent species of phytoplankton in the Bering Sea include *Chaetoceros furcellatus*, *Fragillariopsis oceanica*, *Rhizosolenia hebetata*, *Thalassiosira antarctica*, and *Peridinium pellucidium*. These findings are consistent with data from other authors (19,20). By comparing the species breakdown of phytoplankton,

Table 1

Quantitative assessment of the Bering Sea's pelagic population and biotic balance

	TEST SITES INVESTIGATED										
	South		East		North		West		Mean		For the entire sea
Indices	1981	1984	1981	1984	1981	1984	1981	1984	1981	1984	
Primary production ($g\ C/m^2$ day)	0.32	0.27	0.53	0.43	0.87	1.95	0.49	0.56	0.55	0.80	2.0×10^8 tons C/year
Bacterial production ($g\ C/m^2$ day)	0.58	0.38	0.33	0.36	0.40	0.33	0.29	0.52	0.40	0.40	1.4×10^8 tons C/year
Bacterial destruction ($g\ C/m^2$ day)	1.30	0.86	0.73	0.82	0.86	0.74	0.64	1.20	0.90	0.90	9.0×10^8 tons C/year
Biosedimentation ($g\ C/m^2$ day) (0-100 m)	0.35	0.69	0.18	0.53	0.76	0.82	0.46	0.70	0.44	0.68	1.6×10^8 tons C/year
Phytoplankton biomass ($g\ C/m^2$)	0.60	1.60	1.50	1.00	1.00	2.10	2.20	0.95	1.30	1.40	1.8×10^6 tons C/year
Mezozooplankton biomass ($g\ C/m^2$)	3.70	3.50	5.50	3.50	1.10	1.10	4.00	4.40	3.60	3.10	5.0×10^6 tons C/year
Bacterial plankton biomass ($g\ C/m^2$)	0.52	0.10	0.22	0.16	0.45	0.12	0.24	0.14	0.36	0.13	0.4×10^6 tons C/year
Seston mass (wet weight matter/m^2)	55.0	48.0	96.0	30.0	44.0	165.0	66.0	30.0	65.0	68.0	7.0×10^6 tons C/year
Phytoplankton (P/B)	0.47	0.11	0.56	0.48	0.90	1.00	0.40	0.60	0.58	0.54	--
P/D	0.24	0.31	0.72	0.52	1.00	2.60	0.76	0.47	0.68	0.89	--

which was compiled after processing the samples of the 1981 voyage, with published data, we can conclude that significant modifications in Bering Sea flora have not occurred over the last 30–50 years (19,20).

Soluble levels of carbohydrates, which are the primary products of photosynthesis, were determined at various stations during the 1984 voyage. Carbohydrates are one of the elements excreted by phytoplankton. Therefore, a change in the amount of soluble carbohydrates in the water, or in their proportion to other integral characteristics of the status of the phytoplankton community, would indicate modifications in the functional state of algae and their rate of exchange with the surrounding environment (11,14). The procedures described previously by Josefson and others were used to determine these levels (27). The data obtained are evidence of a relatively negligible heterogeneity for this indicator in the regions under study, and the Bering Sea's high phytoplankton productivity. Carbohydrate levels in the surface layers during the 1984 voyage fluctuated between 6.5 and 12 g/m^2 (Table 2) and averaged two to three times higher than in the Baltic Sea for the summer period (3). As depth increases, carbohydrate levels in the waters of the euphotic zone drop somewhat, totaling approximately 30–50 mg/m^2 in the lower boundary of the photosynthetic zone.

Carbohydrate levels in the water for the Bering Sea averaged 77 percent of primary production, which is evidence of intensive metabolism of the phytoplankton community. These were the first studies of this kind to be conducted in the Bering Sea. Of great importance to advancing our understanding of the mechanisms at play in plankton community functioning is an assessment of carbohydrate levels and of other characteristics reflecting the rate of new formation and destruction of organic matter in this highly productive region of the world's oceans.

As shown in Table 1, mean values for mezozooplankton biomass in the Bering Sea for June 1981 and July 1984 were virtually identical, totaling 36 and 31 g/m^2 wet weight, respectively, for the 0–45 meter layer. Differences in the mean mezozooplankton biomass values for both 1981 and 1984 were also insignificant. Minimum mezozooplankton biomass values (11 g/m^2) were ascertained at the "North" test site, which exhibited an upwelling-induced, intensive phytoplankton growth during the 1981 and 1984 monitoring periods (23,24). Maximum mean mezozooplankton biomass

Table 2

Mean total number of bacteria (TN), their biomass (B), and production of bacterial biomass (P) at test sites in the Bering Sea (Summer 1984)*

Depth	South site			East site			North site			West site		
(meters)	TN	B	P	TN	B	P	TN	B	P	TN	B	P
0.5	169	3.2	8.3	252	4.7	7.2	117	2.2	6.0	110	2.1	13.6
10	115	2.1	8.8	233	4.4	9.9	136	2.5	6.0	178	3.3	8.9
15	115	2.2	9.6	88	1.6	8.0	264	5.0	9.9	277	5.2	11.6
25	100	1.9	9.3	115	2.2	8.4	178	3.3	6.4	201	3.8	13.0
45	120	2.3	6.5	225	4.2	6.8	125	2.3	8.1	83	1.6	10.4
70	165	3.1	3.6	308	5.3	6.1	77	1.4	4.4	80	1.5	7.0
100	117	2.2	5.5	154	2.9	5.3	-	-	-	87	1.6	6.6
125	-	-	-	241	4.5	3.1	-	-	-	-	-	-
150	106	2.0	10.3	-	-	-	-	-	-	67	1.3	4.1
200	85	1.8	7.5	133	2.5	4.2	-	-	-	62	1.2	7.2
500	117	2.2	7.3	80	1.5	4.7	-	-	-	78	1.5	11.5
1000	97	1.8	9.2	121	2.3	3.6	-	-	-	59	1.1	12.6
1500	109	2.0	6.9	98	1.8	-	-	-	-	63	1.2	14.5
2000	99	1.8	3.8	90	1.7	3.8	-	-	-	76	1.4	10.9
2500	119	2.2	3.6	-	-	-	-	-	-	74	1.4	24.5
3000	83	1.6	2.2	-	-	-	-	-	-	90	1.7	10.3
3500	77	1.4	2.2	-	-	-	-	-	-	-	-	-
3900	68	1.3	4.7	-	-	-	-	-	-	-	-	-
Median	109	2.1	6.4	164	2.8	5.1	142	2.7	6.9	105	2.0	11.1

* Values for TN = thousands cl/ml
B = ug C/l
P = ug C/l per day

values in 1981 were observed at the "East" site, and in 1984 at the "West" site. These figures exceeded the lowest average biomass values by almost five-fold. Total mezozooplankton abundance in 1984 fell by 1.5 to two times compared to 1981 levels.

The great abundance and biomass of mezozooplankton organisms in the "North" site were maintained through transport by the Anadyr Current of nutrient- and phytoplankton-rich water. Three fauna groups of phytoplankton are mixed in the "North" site: southern Bering Sea oceanic, northern Bering Sea, and neritic (1,2). In 1981 members of only two of these groups, oceanic and neritic, were found; in 1984 all three groups were present. The nucleus of the southern Bering Sea oceanic group was comprised of copepods (filter-feeders): *Calanus cristatus*, *C. plumchrus*, *Eucalanus bungii bungii*, and *Metridia pacifica*. Typical members of the north Bering Sea group were the crustacean *Calanus glacialis*. The neritic group included the pelagic larvae of benthic organisms, rotifers, and others.

Science currently has extensive information on patterns of phyto- and mezozooplankton development. However, we have only recently begun an in-depth study of microzooplankton; Bering Sea microzooplankton were studied for the first time in 1981. It was established that the bulk of microzooplankton in the Bering Sea inhabits the upper 80-meter layer of water mass. The average biomass for these organisms amounts to two to five grams wet weight under one square meter; infusoria production was approximately two grams wet weight below one square meter of the water surface diurnally.

Findings from 1984 demonstrate that microzooplankton in the Bering Sea include infusoria, flagellates, *Radiolaria*, *Formaninifera*, larval-stage crustaceans, and other small planktoners. The first two groups of organisms are dominant in microorganisms. On the basis of data on the abundance and biomass of these simple organisms, we can conclude that the Bering Sea is a highly productive body of water. Maximum levels for infusoria abundance and biomass amounted to 12×10^6 organisms per cubic meter and 4.4 g/m^3, respectively; for flagellates, these figures were 3.1×10^6 organisms per cubic meter and 0.1 g/m^3. The spatial distribution of microplankton organisms was determined by the interaction of an entire set of conditions: temperature, salinity, and hydrochemical and hydrobiological factors.

As our findings from 1981 have demonstrated, the locations of isolines for infusoria and flagellate biomass at various layers of the four areas in the Bering Sea that we investigated were in most instances consistent with similar isolines for water salinity, flow rates, and nutrient concentrations in the water. Our data provides clear evidence of the potential use of microzooplanktonic organisms as a bioindicator for heterogenous water masses. Primary production and bacterial destruction of organic matter are among the most important functional indices of the state of the marine ecosystem, since their correlation determines the degree to which the processes of new formation and destruction of organic matter are balanced (21,23,24).

The depth of the photosynthetic zone in the Bering Sea during the biological spring and summer of 1981 and 1984 did not exceed 45 meters. Vertical profiles for primary production generally had a single peak in the zone of optimal light conditions (5–10 meters, rarer in surface layers). Phytoplankton production decreased gradually below this maximum figure.

Because of the great heterogeneity of ocean conditions, even the mean values for primary production of organic matter in the investigated areas of the Bering Sea fluctuated appreciably (from 0.3 to 2.0 grams C/m^2 per day). These fluctuations were significantly greater than the value for bacterial destruction of organic matter in the photosynthetic zone: 0.6 to 1/3 g C/m^2 per day (Table 1). The high variability in the values for primary production of organic matter (more than 100-fold) and high P/B phytoplankton coefficients (0.9–1.0) were observed in the "North" site adjacent to St. Lawrence Island. These factors—the abundance of plankton organisms, low water temperature, the large supply of nutrients, and the high distinct activity of phytoplankton—are evidence of the presence of continuous upwelling in this part of the Bering Sea during the summer. Average primary production figures for the remaining areas and their fluctuation limits were considerably lower (Table 1).

Organic matter formed through photosynthesis by phytoplankton is immediately incorporated into the destruction cycle (15,18). We know that approximately 20 percent of newly synthesized organic matter is used in algae metabolism. Roughly 65 percent of newly formed organic matter is mineralized to carbonic acid and mineral salts by microorganism vital activity. Only a negligible portion of organic matter is broken down through the vital activity of zooplankton and is also removed from the active zone through biogenic sedimentation.

Analysis of the material obtained indicates that the rates of bacterial destruction of organic matter in the Bering Sea areas under study varied considerably in the 0–45 meter layer; they tended to change toward the lower boundary of the euphotic layer. In 1981 relatively high levels of bacterial destruction were observed in the "South" site, while other areas of the Bering Sea exhibited lower destruction rates. In 1984 maximum destruction rates (1.2 g C/m^2 per day) were recorded in the "West" site, and minima (0.74 grams C/m^2 per day) were found in the "North" site (Table 1). The rates of bacterial destruction during the 1981 and 1984 voyages were high (0.6–1.3 grams C/m^2 per day) in the "East," "West," and "South" sites. They exceeded by 1.5–3 times the values of photosynthesis of organic matter in the water column below one square meter. The "North" site alone differed in this respect. Bacterial destruction values were equal to or even 2.5 times lower than the average figures for primary production in the entire photosynthetic zone.

The rate of organic matter destruction dropped considerably with increases in depth. The rate of destruction in the euphotic zone was, as a rule, two to three times greater than in deep layers of the water column. This fact is evidence that the bulk of newly synthesized organic matter is decomposed in the photosynthetic zone, and only an insignificant portion in deep water layers.

A comparison of average values for organic matter production and destruction (averaged for the entire Bering Sea from the data obtained during the 1981 and 1984 studies) indicates that these processes maintain considerable interannual stability. This is true since bacterial destruction rates encountered in 1981 and 1984 were virtually identical. Furthermore, the figures for primary phytoplankton productivity were very close (Table 1).

Mean values for the P/D coefficients for different test areas point to the transitional state of the plankton community, from the biological spring to biological summer in 1981, and in 1984 from the biological summer to biological autumn.

We attempted to calculate the value for production and destruction in the entire sea for the vegetation period using measurements of primary production and bacterial destruction of organic matter. We incorporated data from McRoy and Goering for these calculations, according to which 45 percent of the total amount of organic matter production occurs during the first 60 days of spring (29). The total yearly production of phytoplankton in the Bering Sea amounted to 2.0×10^8 tons of C organic matter, approximately 1/150 of total organic matter produced in the world's oceans for one year (10). Bacterial destruction of organic matter in the 0–100 meter layer was 9.5×10^8 tons C per year.

New data were obtained during the 1984 expedition, and we can compare the rate of microbial oxidation and biogenic sedimentation of organic matter. The findings of our observations demonstrate that the rate of organic matter destruction exceeds by an average of two to two and one-half times the rate of its removal from the active zone during biogenic sedimentation. Destruction of organic matter totalled 13.7–66.3 mg C/m^2 per day in the Bering Sea in the summer of 1984. Biogenic sedimentation amounted to no more than 5.9–20.3 mg C/m^3 per day.

MICROFLORA AND MICROBIOLOGICAL PROCESSES

Microorganisms are the most active component of marine ecosystems. They exhibit highly diverse physiological and biochemical activity, they have a high reproduction rate and considerable adaptative potential, and they play an important role in how these ecosystems function. We can determine water quality based on their total abundance, their biomass, and other microbiological indices, including their trophic level and the extent of contamination. Depending on the phenomena in question, microbial populations can serve as indicators of physical and chemical processes, or act as a powerful biological factor to trigger the removal of organic pollutants from the marine environment.

Until the last few years, no microbiological field studies had been conducted in the open ocean areas of the Bering Sea. This kind of investigation was initiated in the summer of 1981 during the comprehensive Soviet-American ecological expedition. Microbiological investigations were continued and expanded during the second expedition in the summer of 1984. These studies indicate that the waters of the Bering Sea in the summer of 1984 were characterized by low total numbers of bacteria (TN)—59–308,000 cl/ml; low biomass of -1.1–5.3 ug C/liter; and comparatively low diurnal bacterial production of 2.2–24.5 ug C/l. (Note that "cl" indicates cells.) These values correspond to oligotrophic waters.

Bacterial plankton distribution in the areas we investigated was uneven in the vertical profile of the water column. The concentrations of bacteria and its biomass at the "East" and "North" sites were somewhat higher than for "South" and "West" (Table 2). These discrepancies apparently were due to a number of factors including non-uniformity of the water masses and the rate of phytoplankton production of organic matter.

Factorial analysis of the dependency between bacterioplankton growth rates and various ecological factors such as water temperature and salinity indicate that the elevated mean values of TN and microflora biomass (194,000 cl/ml and 3.6 ug C/l, respectively) were confined to a temperature interval of 6.8–9.6°C in water with a salinity of 32.3–33.3 percent. A second temperature interval conducive to plankton bacteria growth lay within the relatively low ranges of 1.2–4.0° C. This fact explains the characteristic physiological properties of Bering Sea microorganisms.

We observed a characteristic pattern for vertical profiles of the water column in deep water areas: as depth increased, a gradual drop in microflora abundance, biomass, and activity was observed. We discerned some increase in bacterial population density only at specific depths. Two local maximum microorganism concentrations were established. The first was in the surface film where bacteria abundance and biomass were one order higher than in samples taken from the underlying water layer. A specific set of microorganisms (bacterioneustons) growing at the ocean/atmosphere interface constitutes the first biological structure which transforms and degrades many chemical substances localized in the ocean's surficial film (5,6). The accumulation of microorganisms in this microbiotope is a function of specific physical and chemical factors which foster intensive microorganism reproduction, and the comparatively low rate at which zooneustons consume them.

The subsequent layer with increased bacteria abundance and biomass was situated at the "North" and "West" sites at a depth of 15 meters in the pynocline. Phytoplankton swarming was detected here, and the water was consequently enriched with the products of its metabolism. We observed some increase in TN and bacteria biomass at the "South" and "East" sites at a depth of 70 meters. This kind of bacterioplankton distribution is coupled with the multi-layer, vertical structure of the water masses and points to broad possibilities for the microbiological indication of variegated water masses.

The rate of diurnal production of bacterial biomass in the majority of areas studied was roughly uniform (2.2–10.3 ug C/l), with the exception of the "West" site. Microflora activity in this area was considerably higher (4.1–24.5 ug C/l per day) than in the other delineated areas (Table 2). As the depth increased, the rate of diurnal bacterial production did not decline; instead, it increased to maximum mean values (24.5 ug C/l) at a depth of 2,500 meters. These fluctuations in the rate of bacterial production in the water column of the area in question were apparently due to chemosynthesis, which in anaerobic conditions is prevalent over heterotrophic CO_2 assimilation by bacteria.

The portion of bacterial production as compared to phytoplankton primary production in the photosynthetic zone in 1984 displayed a mean increase over the test sites from 18.8 percent to 91.4 percent. In 1981 this correlation fluctuated between 0.5 percent and 150 percent. It should be noted that the correlation of bacterial production to primary production in the Peruvian near-coastal and other regions of the world's oceans varies between three percent and 75 percent (22). Mean TN and microorganism biomass values in 1984 were one and one-half to three times lower than in 1981. This may be a function of interannual fluctuations in the quantitative composition of microbial populations.

Many bacteria exhibit tremendous flexibility in their utilization of organic matter. Functional and active enzymes of preparatory metabolism underlie a microorganism's adaptation to new food sources. Regulatory and structural genes already present in the cells undergo alterations (9). Microorganisms have the ability to synthesize only those enzymes which are essential for decomposing specific substrata (e.g., in specific physiological conditions). This is both expedient and efficient (24). Microflora which adapt to new chemical conditions and utilize certain compounds are widely used as a biological indicator of the marine environment.

On the basis of investigations of different physiological groups of marine microflora initiated in the expedition in the summer of 1981 and followed up in the summer of 1984, we were able to establish the following: parallel to heterotrophic saprophytic microflora, which are able to assimilate easily oxidized organic matter, we also detected toxic organic compounds decomposing bacteria in the microbial landscape of the open waters of the sea. These compounds include natural elements, such as petroleum aromatic hydrocarbons (benz(a)pyrene or BP) and anthropogenic xenobiotics such as polychlorinated biphenyls (PCBs). We shall tentatively designate these forms of microorganisms as indicators.

Microbiological investigations indicate that there is an uneven distribution of both heterotrophic saprophytes and bacteria indicator groups for the areas under study and the layers of the water column.

The most probable number (MPN) of heterotrophic saprophytic bacteria in the summer of 1984 varied from 0–10^4 cl/ml. Furthermore, 67 percent of the samples processed from various layers of the water column contained from several to tens of bacteria cells per ml of water. We detected hundreds of cells in 19 percent of the samples, and only two percent showed thousands of cells per ml of water. The variability limits for MPN of saprophytes indicated above were consistent for all sites, with the exception of the "North" site, where Sacrophyte MPN totalled 0–10^3 cl/ml. The active saprophytic heterotrophic microflora amounted to 0.003–40 percent of the total bacteria count in different water samples.

In the summer of 1981 saprophytic bacteria MPN exhibited zero values in 68 percent of our samples. This indicator dropped to 12 percent for the summer of 1984. Sacrophytic bacteria MPN variability limits for 1984 in comparison to 1981 rose in all sites by one order of magnitude. Three zones with increased concentrations were detected in the vertical distribution of heterotrophic saprophytic microflora for the summer of 1984: the 15–25 meter (thermocline), 100–150 meter, and 1,000–1,500 meter zones.

Based on our findings from the 1981 voyage, we established the first taxonomic composition for heterotrophic saprophytic bacteria detected in the open regions of the Bering Sea (8). These studies demonstrated that the following families dominate the composition of the Bering Sea's microbial topography: *Bacillaceae*, *Bacteriaceae*, *Micrococcaceae*, and *Pseudomonadaceae*. The following families were observed in significantly lower numbers: *Mycobacteriaceae*, *Lactobacillaceae*, *Vibrionaceae*, *Corynebacteriaceae*, *Halobacteriaceae*, and *Neisseriaceae*. The most widespread microorganism species were: *Bacillus sp.*, *Pseudomonas sp.*, *Planococcus sp.*, *Bacterium sp.*, and *Micrococcus sp.*

The abundance of indicator petroleum hydrocarbon-oxidizing microorganisms fluctuated between 0 and 10^4 cl/ml in 1984, but in most samples abundance range was from 1–10 cl/ml. Hydrocarbon-oxidizing microorganism distribution for 1981 in both the areas under investigation and the layers of the water column was highly uneven; from 83 to 97 percent of the samples from the different sites contained no bacteria from this group. In 1984 we detected zero-value concentrations of hydrocarbon-oxidizing bacteria in only 3–14 percent of our samples. Maximum abundance for this microorganism group in both 1981 and 1984 was observed in the "West" test site.

Distribution of BP-oxidizing microflora which can utilize polycyclic aromatic hydrocarbons was essentially similar to heterotrophic saprophytic bacteria distribution. MPN for this group of bacteria at the "West" site varied from 0–10^4 cl/ml, which amounted to tens of cells (45 percent of samples) and 0–10 cells (39 percent of samples) per one ml of water. The range of abundance variability for the "South" and "East" sites was from 0–10^3 cl/ml. "North" site MPN of BP-oxidizing bacteria fluctuated within an even narrower range of 0–10^2 cl/ml.

BP-oxidizing microorganism distribution for the different test sites was greater in 1984 than in 1981. While zero MPN values of these bacteria for 1981 at the different sites totaled 81–97 percent of the total number of processed samples, this indicator dropped sharply in 1984, ranging from four percent ("West") to 10 percent ("East").

The study of PCB-utilizing heterotrophic bacteria is of particular interest for several reasons. First, industry and agriculture use chlorinated hydrocarbons more ubiquitously every year, with concomitant increases in their flux into the marine environment. Secondly, PCBs are quite stable and are virtually chemically nondegradable in natural conditions. At the same time, contamination of the marine environment by this class of chemical compounds poses a serious problem in that chlorinated hydrocarbons not only exert a highly toxic effect when they interact with the marine biota, but they also clearly exhibit carcinogenic and mutagenic properties.

MPN for PCB-oxidizing bacteria at test sites "South," "East," and "North" reached thousands of cells per one ml of water. At the "West" site this figure rose as high as tens of thousands of cells per ml of water. At the same time, we detected zero MPN values for these bacteria at different water column layers. In a number of instances, particularly at the "North" site, we observed a rise in MPN in the near-surface and near-bottom water layers. As a whole, the abundance of PCB-oxidizing microorganisms for both the summers of 1981 and 1984 was one or several to tens of cells per ml of water. Their vertical distribution was similar to BP-oxidizing microflora distribution.

From concurrent analysis of TN for microorganisms and of MPN for PCB-oxidizing and BP-oxidizing bacteria we determined that in most instances the following pair values for the above parameters in our processed water samples were prevalent: when TN = 0–100,000 cells per ml, MPN of PCB- and BP-oxidizing bacteria = 1–10 cells per ml (25 percent and 25.5 percent of samples, respectively), and 10–100 cells per ml (16 and 18 percent of samples); when TN = 100–200,000 cells per ml, MPN of PCB- and BP-oxidizing bacteria = 1–10 cells per ml (15 and 17 percent of samples). In other words, MPN for PCB- and BP-oxidizing microorganisms showed virtually identical percentages of total microorganism abundance. This fact indicates that many marine bacteria apparently possess polyfunctional enzymatic activity, allowing them to adapt rapidly to habitat alterations.

Tolerance or resistance mutations permit microorganisms to grow in contaminated conditions and perform microbial oxidation of toxic organic substances. Coding is usually performed by either chromosomal genes or by genes located on the extrachomasomal DNA elements to which plasmids belong. Plasmids are considered a key factor in microbial cell adaptation to unfavorable ambient conditions. During *ad hoc* experiments to investigate microbial resistance to heavy metal salts and antibiotics, we found that many bacteria strains isolated in the open areas of the Bering Sea contained plasmids (24).

Mutations of many microorganisms which come into contact with contaminants have yet to be investigated. This area of research is crucial for the Bering Sea. Due to low temperatures, microbial oxidization is essentially the sole process in the elimination of organic contaminants—petroleum hydrocarbons, in particular—in this region of the world's oceans.

BIOGEOCHEMICAL CYCLES AND ORGANIC CONTAMINANTS

The study of contaminant biogeochemical cycles is an important scientific problem which merits independent investigation. It touches upon different media of the biosphere and encompasses the major processes involved in the functioning of living matter. In addition, it treats many properties of non-living matter.

Within the concept of marine ecosystem assimilative capacity, the aim of studying contaminant biogeochemical cycles is to compare mass balances and determine the lifetime of contaminants in the ecosystem (7). This objective calls for an interdisciplinary approach to our work, which can be broken down as follows:

- Determine contaminant concentrations in ecosystem components;
- Assess biosedimentation rates;
- Study contaminant fluxes at ecosystem boundaries;
- Evaluate microbial organic contaminant oxidation rates.

Polycyclic aromatic hydrocarbons (PAHs) of both natural and anthropogenic origins head the list of the many organic compounds which are released into the environment and induce chemical changes. With considerable molecular stability and high carcinogenic and mutagenic effects, this type of compound poses a serious threat to the vital functions of marine organisms.

In view of existing PAH determinations in both crude oil and its refined products (which for BP are several millionths of the oil's mass), we can postulate that petroleum contamination is a powerful factor which disperses PAHs throughout the world's oceans. Some estimates put BP release into the marine environment from petroleum hydrocarbon leaks during shipping alone as high as ten tons per year, while its input into the ocean's surface by atmospheric deposition occurs at a rate of 30 tons annually. Natural sources of BP input, particularly volcanic flow, amount to only 1.2 tons per year.

The study of the BP biogeochemical cycle in the Bering Sea ecosystem was initiated in 1981 and was resumed in 1984 (23,24). Twenty-six stations in different areas of the Bering Sea were monitored during this period. BP was present in all the water samples processed, fluctuating between one and 1,000 ng/l. However, this figure did not exceed 10 ng/l in the great majority of cases in the 0–100 meter water layer (including the surface microlayer—SML).

BP levels at the "South" test site varied from 1.3–36.8 ng/l (10–14 ng per liter in the SML). While overall background BP levels were low (2–5 ng/l) at depths of ten meters and deeper in the water column, we detected maximum BP concentrations were 34–36 ng/l in the site's southern portion near Blizhny Island at a depth of 45 meters.

BP levels for the "East" site (1–46 ng/l) were on average lower than for the other test areas at the different depths and were fairly uniform. The site's maximum value (46 ng/l) was detected at 45 meters in the southeastern portion.

The "North" site displayed fluctuations in BP levels in the water (not including maximum values) of one to 17 ng/l; its SML ranged from one to 12 ng/l. Maximum BP levels were obtained in the site's northeastern section adjacent to St. Lawrence Island, where BP concentrations were 1,000 ng/l in the SML, and 900 ng/l at the 25 meter depth. These levels resulted from the presence of PAHs in oil films and in contaminant discharges.

The water's surface microlayer in the "West" site showed BP levels of 2–43 ng/l (with an average of 22 ng/l). BP levels in the water column varied between three and 15.5 ng/l. We recorded mimimal BP concentrations in the water at a depth of 500–2,000 meters for both sides of the submerged Shirshov chain.

For the Bering Sea at large, BP concentrations in the water ranged from 0–46 ng/l. BP distribution in surface microlayer waters exhibited a high observed frequency of minimum concentrations (82 percent of samples). In addition, this BP figure did not exceed 5 ng/l in one-third of our samples.

Except for rare cases, any significant BP buildup in the underlying water layers (to 100 meters) was absent. Accumulation was minimal, up to 16 ng/l, in 87 percent of our samples; as depth increased it fell to zero. Spatial BP distribution in 1984 generally showed low concentrations. What is especially important is that increased BP abundance (20 ng/l and higher) was localized to specific zones. Vertical BP distribution was uniform; in certain cases we detected BP accumulation in the SML and at 45 meters.

Total BP levels in Bering Sea waters, particularly in the SML, were one to two orders of magnitude lower in 1984 than in 1981. Vertical distribution was decidedly uniform. However, we found maximum BP concentrations at the "North" site in both 1981 and 1984 .

Examination of our samples of bottom sediment from depths of 40 to 4,000 meters indicated general PAH accumulation in this component of the Bering Sea ecosystem at all test sites. The BP level in the ten centimeters of the bottom closest to the surface fluctuated between 80 and 2,160 ng/kg dry weight, with a mean value of 250 ± 40 ng/kg dry weight (i.e., equal to 10^{-1} ug/kg dry weight). This is two to three orders of magnitude lower than the BP accumulation levels in bottom sediment of impacted areas of the Baltic Sea.

Maximum BP levels of 2,160 ng/kg dry weight were detected in the bottom sediment of the "East" site . "North" bottom sediment and deep water "West" bottom sediment contained less BP: an average of 270 ng/kg dry weight and 160 ng/kg dry weight, respectively. Mean BP accumulation in Bering Sea bottom sediments in 1984 compared to 1981 amounted to 37 percent, and in some cases, five percent.

In 1984 BP was present in all of our plankton organism samples. There was, however, a fairly narrow range of concentrations, from 1,200 to 17,500 ng/kg dry weight. The most homogenous

BP level (3,000–3,600 ng/kg dry weight) was detected in plankton from the "East" site; the maximum BP value was found in plankton collected from the "North" test site at stations adjacent to St. Lawrence Island. On the whole, the level of BP bioaccumulation by plankton was two to three orders of magnitude lower than what we had found in 1981 (accumulation coefficient of 10). However, the overall trend of BP accumulation in the biota remained unchanged.

Ten-day simulation of BP microbial destruction in experiments most closely approximating *in situ* conditions has pointed to the potential ability of microbial populations in the Bering Sea to transform from seven to 66 percent of BP which is input in initial concentrations of 1,000 ng/kg. This is consistent with its maximum possible concentration in sea water. Microflora from the "North" site showed the highest biodegradation capacity for BP, both from the 0–25 meter and particularly from the surface microlayer (59 percent of the BP which was input underwent transformation). Our experiments demonstrated the ability of deep-water microflora (depths of 500 meters in the "East" site) to transform BP.

BP circulation was generally found to be lower in those elements of the Bering Sea ecosystem which were studied in 1984 than it had been in 1981. However, the active circulation of BP in the Bering Sea ecosystem and its presence in the composition of the permanent hydrochemical background over a number of years indicate that this area of the Pacific Ocean is a receptor for intensive PAH fluxes. In view of the remoteness of our Bering Sea test sites from major industrial zones and the organic nature of PAH anthropogenic input, long-range atmospheric transport of contaminants and certain natural sources clearly play a key role in the formation of existing BP levels in the marine environment. These include PAH fluxes of volcanic and petroleum origins.

Chlorinated hydrocarbons such as pesticides (COPs) and polychlorbiphenyls (PCBs) figure among synthetic pollutants which have become ubiquitous in the environment. Primary pathways of chlorinated hydrocarbon input into the marine environment include continental surface runoff (particularly with river water) and atmospheric transport via dry deposition or precipitation. The gravity of ocean contamination from chlorinated hydrocarbons, and particularly from PCBs, is underscored by the fact that of the 370,000 tons of PCBs currently distributed throughout the environment, 231,000 tons (i.e., over 60 percent) are concentrated in ocean ecosystems. Furthermore, 230,000 tons of this amount are in ocean water (33).

Scientific information on PCB levels in sea waters (particularly in open ocean) is extremely limited (25,32,34,35). This is due to the fact that determining PCB levels in the ocean's ecosystems tests the very limits of the sensitivity of today's analytical technology.

At the same time, chlorinated hydrocarbons as nonpolar compounds are easily dissolved in fats. As a result, they rapidly accumulate in hydrobionts and in ocean water's surface microlayer where organic compounds are concentrated.

Current research indicates that the mean PCB concentration in ocean water totals 0.1 ng/l in the Atlantic Ocean, 0.14 ng/l in the Indian Ocean, and 0.05 ng/l in the Antarctic Seas (25,30,32,33,34,35). The only scientific information regarding PCB distribution in the Bering Sea is from research conducted in 1981, which put mean PCB concentrations at 0.10 ng/l (34).

As the findings from our studies conducted in the summer of 1984 have indicated, the anthropogenic burden on the world's oceans has also impacted the status of the Bering Sea. PCB levels ranged from 0.5 to 0.8 ng/l in all the samples taken. This is typical for impacted areas of the world's oceans. The highest chlorinated hydrocarbon levels were found in zones with relatively intense shipping. Lowest levels were found in the Bering Sea's subpolar region.

Analysis of ichthyofauna demonstrated that the maximum uptake of chlorinated hydrocarbons occurs in the livers of fish. PCB levels in pollack liver samples ranged from 2.7 to 44.4 ng/g wet weight, with an average of 9.5 ng/g. Chlorinated pesticide levels—the DDT group—ranged from 0.2–8.0 ng/g wet weight (mean value of 2.5 ng/g). The 4.4'-DDT component was prevalent in the samples, which is evidence of the metabolic processes occurring directly in the organs of fish. Other organs with lower fat content consequently accumulated lower CH levels expressed in ng/g wet weight: muscle tissue = 0.2–1.2 DDT and 1.2–5.9 PCB; gonads = 0.2–1.2 DDT and 1.1–6.1 PCB; spleen = 0.2–1.0 DDT and 2.2–5.1 PCB; cerebrum = 0.2–0.9 DDT and 2.2–5.1 PCB; and branchiate arc = 0.2–1.4 DDT and 2.2–8.5 PCB.

The correlation of DDT-group components in these organs was more balanced. Highly chlorinated components were present in both PCB components (penta- and hexachlorbiphenyl) and liver samples. This can be attributed to their lower rate of transformation in biological targets.

Chlorinated hydrocarbon accumulation was even more pronounced in benthic organisms. During the 1984 expedition we took benthic samples at ten stations situated in different test sites and cross sections of the Bering Sea to determine chlorinated hydrocarbon levels. DDT-group levels in these samples fluctated from three to 49 ng/g wet weight, and polychlorbiphenyls from 21 to 102 ng/g wet weight. The content of weakly and highly chlorinated biphenyls was balanced in the PCB fraction, while the DDT fraction showed a prevalence of the 2.4'–4.4' DDE components. This was apparently due to the fact that benthic organisms consume partially dehydrochlorinated DDT mixture.

Our investigations failed to establish the dependency of chlorinated hydrocarbon levels in benthic organisms on CH levels in bottom sediments. Contamination of the uppermost layer of bottom sediments by chlorinated hydrocarbons for all of our sites was fairly uniform and totalled 0.3–3.4 ng/g dry weight for DDT, and 0.5–9.2 ng/l wet weight for PCBs.

Our studies of chlorinated hydrocarbons in various parts of the Bering Sea ecosystem have demonstrated that DDT- and PCB-group compounds are absorbed by plankton. We detected a prevalence of weakly-chlorinated forms among the PCBs; 2.4'-olefins were prevalent among the DDT components. These findings are clearly consistent with the characteristics of plankton habitats.

PCB lifetime in Bering Sea waters was ascertained by gas chromatographic analysis. Lifetime for various PCB components was from 3.5 years for monochlorbiphenyls to 42 years for decachlorbiphenyls, depending upon the extent of chlorination.

Drawing from our study of the correlation of PCB components in biotic and abiotic elements of the Bering Sea ecosystem, we have forecasted a 1.5–1.7 fold increase of PCBs in the biotic component by the year 2000. This could negatively affect the Bering Sea's biological resources and disrupt the genetic fund of its hydrobionts.

ECOLOGICAL AND TOXICOLOGICAL RESEARCH

The task of setting ecological standards to regulate man's impact on the world's oceans and their different regions calls for establishing the critical load the marine ecosystem can tolerate and an assessment of its assimilative capacity (1,7). Such an assessment requires information on the biotic balance of the ecosystem under investigation, as well as information on the "critical" concentrations of various pollutants in ocean waters (7). By "critical" concentrations of a contaminant we mean the level at which even a minor additional impact could trigger an irreversible reduction in the tolerance level of the biological process selected as the "target." The tolerance limit of this process, or of that portion of the ecosystem under investigation, is in this instance determined by that state of the ecosystem at which any alteration is still reversible.

Determination of the "critical" levels of various contaminants is extremely complex. However, current literature on the subject has already accumulated an abundance of factual material on the toxic impact of heavy metals, polychlorinated biphenyls, and polyaromatic compounds (16,17). The wide variability in toxicity of some toxicants, which is contingent upon ecological alterations in the particular body of water, is one of the primary complexities in actually determining "critical" levels of contaminants vis-a-vis a selected ecological "target." Current data indicate that the inhibitory effect of various contaminants on plankton is to a large degree a function of the period of seasonal plankton organism succession (12).

During the expedition in the summer of 1984, ecological and toxicological experiments were conducted to determine the properties of both the individual and combined impacts of heavy metals on primary production of organic matter and microzooplankton abundance. From these experiments, which approximated *in situ* conditions, we established the variability ranges for "critical" levels of copper (2–4 ug/l) by analyzing the combined impact of heavy metals on primary production and soluble carbohydrate levels in water. These values were approximately two- to four-fold greater than the maximum copper ion levels in Bering Sea euphotic zone waters.

During the voyage we also conducted ecological/toxicological sensing of the Bering Sea's pelagic zone. Soviet-American experiments were also run to study the combined impact of heavy metals and nutrients on the plankton community.

Analysis of our findings has demonstrated copper's greater toxicity in comparison to cadmium in terms of phytoplankton and microrganisms. LD_{50} and EC_{50} levels in different areas were not uniform. Short-term modeling experiments demonstrated an increase in phytoplankton tolerance and a decrease in infusoria resistance to test copper additions with increasing depth of water samples taken for the experiment (0 to 25 meters). The presence of a negative, inverse relationship through the bacterial chain between trophic groups of hydrobionts clearly explains the contrasting propensity of phytoplankton and infusoria for fluctuations in resistance to injections of heavy metals. The greatest phytoplankton resistance and the greatest infusoria vulnerability to copper were detected at the stations in the "North" site. Mean LD_{50} and EC_{50} values at the different Bering Sea test sites equaled 7–10 ug/l Cu. The combined impact of copper and cadmium additions on phyto- and microzooplankton was additive when levels of both metals in the water were below 25 ug/l, and synergistic at higher levels.

Comparison of ecological and toxicological experiments conducted in both the Bering and Baltic Seas points to a comparatively high vulnerability of the Bering Sea ecosystems to heavy metals. During our Bering Sea studies and similar projects conducted in other regions of the world's oceans, it has been found that the direct dependency between carbohydrate levels in the water and the values of primary production is disrupted when heavy metal levels approach "critical" (14). Clearly, this is evidence of perturbed algal exchange under the toxic impact of these metals.

As we mentioned above, microorganisms play an extremely important role in the destruction of organic matter in the Bering Sea and in subarctic zones of the world's oceans. Therefore, perturbation from anthropogenic contaminants of the normal functioning of natural microbial populations may irreversibly alter the ecosystem of these seas. Assessing the "critical" levels for the impact of various contaminants on bacterial production is therefore extremely important. With this objective in mind, the second Soviet-American Bering Sea expedition conducted model experiments in what closely approximated *in situ* conditions. Analysis of our findings has shown that at PCB, BP, octadecan, and acetone concentrations of 1-10 ug/l, bacterial biomass production rose in most cases by 1.5–7-fold in comparison to the control. At concentrations of 100 ug/l, bacterial activity was inhibited, with productivity falling to levels considerably lower than those of the control. However, in certain sites microbe population activity was also inhibited when injections of toxic organic compound concentrations equaled 10 ug/l. This fact is clearly coupled with varying ecological conditions which determine microbial oxidation rates of organic contaminants (24).

SCIENTIFIC APPROACHES TO DETERMINING THE ASSIMILATIVE CAPACITY OF THE BERING SEA ECOSYSTEM

In summarizing the above discussion, we should stress the importance and timeliness of the research conducted during the second Soviet-American expedition from the standpoint of studying new processes in the Bering Sea, assessing the state of this medium, and developing long-term observations concerning this subarctic ecosystem's assimilative capacity.

Marine ecosystems possess a broad range of physical, chemical, and biological mechanisms through which contaminants can be released from the marine environment without seriously disrupting biogeochemical cycles or affecting the biota. Yet when contaminants reach a certain level in the environment which exceeds the ecosystem's assimilative capacity, they affect hydrobiont survival rates, reproduction, growth, and motor activity. As a result, distribution and quantitative parameters of populations are altered, with possible modifications in the biogeochemical cycles of chemical compounds and the ecosystem's energy budget. The need for quantifying the entire system of processes which determine the "release" rate of contaminants from the ecosystem is today becoming increasingly evident. Of equal importance is quantifying the ability of biological systems and organisms to adapt to new chemical conditions in the ocean. Analysis of the aforementioned processes is reflected in the concept of the assimilative capacity of the world's oceans (7).

The following premises regarding the assimilative capacity of oceans are of paramount importance to an assessment of the Bering Sea ecosystem in this regard:

- The assimilative capacity of the marine ecosystem under study for any contaminant, or aggregation of contaminants, is the maximum dynamic capacity for that amount of contaminants which, over a given unit of time, may be accumulated, decomposed, transformed (chemically or biologically), and released (via sedimentation, diffusion, or any other process) from the ecosystem without perturbing its normal functioning. With this definition, assimilative capacity acquires the dimension of a contaminant flux (e.g., mass related to a unit of time).

- Any marine ecosystem occupies a limited volume which can be clearly delineated; consequently, the assimilative capacity of such a concrete ecosystem has a finite value for the objectively existing property of the marine environment.
- This value can be practically determined by integrated studies and monitoring of the marine environment.
- Determination of the assimilative capacity of marine ecosystems is an essential starting point for subsequently setting standards for external impacts on marine ecosystems and for predicting anthropogenic alterations of the marine environment's ecology.

A generalized ecosystem assimilative capacity model can be recommended on the basis of available scientific information on the Bering Sea ecosystem and the primary conclusions of integrated ecological investigations in this basin. The first stage of research with such a model would establish the rate of contaminant circulation within and removal from the Bering Sea ecosystem. Assimilative capacity is determined in relation to this rate for toxic metals, PCBs, and benz(a)pyrene. PCB and BP circulation rates and accumulation levels have already been determined for various areas of the Bering Sea.

The second stage would entail an analysis of the biotic balance in the Bering Sea ecosystem. Biomass values for the major trophic groups of hydrobionts and their product characteristics have recently been established. It is estimated that the bulk of organic matter in the Bering Sea is formed through plankton microalgal growth. At the same time, these organisms are among the most sensitive to contamination. Therefore, Bering Sea phytoplankton could be selected as the most sensitive link—the ecological "target." Its perturbation by anthropogenic impacts could result in the transformation of the ecosystem as a whole.

The third stage would serve to derive the "critical" levels of the impacts of those pollutants under consideration on the primary production of organic matter of the ecological "target"—phytoplankton. The preceding section of this report cited the findings of ecological and toxicological experiments aimed at determining the individual and combined impacts of certain heavy metals on primary production of organic matter in the Bering Sea. It was established that the limits of variability for "critical" copper concentrations lie between two and four ug/l. We propose subsequently establishing "critical" levels for other heavy metals and for polychlorinated and polyaromatic hydrocarbons. The assimilative capacity of the Bering Sea ecosystem for the most noxious contaminants will therefore be calculated from contaminant balances and from an evaluation of ecological contamination criteria.

Quantification of assimilative capacity is an integrated problem which can only be performed for the most thoroughly studied regions of the world's oceans. Most of the enclosed and semi-enclosed seas belong to this category. These areas are, as a rule, subject to the greatest anthropogenic impacts and are actively used commercially.

ACKNOWLEDGEMENT

The authors would like to convey their gratitude to M.V. Ventsel' and A.S. Kulikov, junior research associates in the Ocean Monitoring Division of the Environment and Climate Monitoring Laboratory, for contributing materials on the quantitative and qualitative composition of Bering Sea phyto- and zooplankton.

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Monitoring Coastal Water Environmental Quality: The US National Status and Trends Program

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Oceans play a major role in the economy of the United States, especially in coastal areas where many of the major US population and industrial centers are located. They provide a thoroughfare for domestic and international shipping, supply fish for food, furnish extensive opportunities for recreational activities, and serve as a site for disposal of wastes.

In the past twenty years, however, it has become more and more obvious that ocean resources are being degraded through uncontrolled development and conflicting uses. This degradation is especially serious in relation to the utilization of oceans for waste disposal. Sewage wastes from municipal waste treatment plants, organic and inorganic wastes of many kinds from industrial sources, hydrocarbon wastes from transportation activities, waste heat and chemicals from power generation, and pesticide and fertilizer wastes from agriculture all enter the marine environment.

These wastes generally cause little harm in trace quantities. However, as more and more wastes find their way into the ocean, the concentrations of the substances they contain build up. This is of particular concern in estuarine and other protected coastal areas where waste inputs are usually concentrated and where the dispersion and dilution which occur rapidly in the open ocean are retarded by restricted interchange with general oceanic circulation.

As concentrations increase, certain heavy metals, synthetic organic compounds, plant nutrients, and other substances contained in wastes reach levels which can cause undesirable environmental effects. Many of the metals and synthetic organics are toxic and cause decreases in populations of important sensitive species, either through direct toxicity or through more subtle but still damaging effects on basic characteristics such as reproduction and behavior. These wastes also often contain high levels of plant nutrients, especially phosphorus and nitrogen. Increased concentrations of these elements can lead to nutrient overenrichment and excessive biological activity, with resultant major changes in chemical conditions and large shifts in the types and amounts of various marine organisms.

Recognizing that the coastal environment of the United States was being threatened by such degradation, in 1984 the US National Oceanic and Atmospheric Administration (NOAA) initiated a national monitoring program for marine coastal waters called the National Status and Trends (NS&T) Program. The purpose of this program is to make systematic observations in carefully selected locations, using meaningful indicators of coastal marine environmental conditions in order to detect changes in environmental quality. With an initial focus on toxic substances, the specific objective of the program is to quantify the current status and long-term trends in the concentrations and effects of toxic chemicals in bivalve mollusks, bottom-feeding fish, and sediments in estuarine and other coastal areas. This information will then be used to assess marine environmental quality and to recommend governmental action to maintain and improve the marine environment. This paper provides a summary of this monitoring program and presents examples of initial results that have been obtained.

STRUCTURE OF THE PROGRAM

The overall direction of the NS&T Program is provided by the Ocean Assessments Division of NOAA's Office of Oceanography and Marine Assessment. However, as illustrated in Table 1, the program is a cooperative effort involving a number of other components of NOAA as well as several nongovermental participants.

The NS&T Program is composed of the following six components:

1. Benthic Surveillance
2. Mussel Watch

Table 1

Principal participating organizations in the National Status & Trends (NS&T) Program

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<u>Program Management</u>:

NOAA: National Ocean Service, Office of Oceanography & Marine Assessment
- Ocean Assessment Division, Rockville, Maryland

<u>Benthic Surveillance</u>:

NOAA: National Marine Fisheries Service
- Northeast Fisheries Center, Woods Hole, Massachusetts
- Southeast Fisheries Center, Miami, Florida
- Northwest and Alaska Fisheries Center, Seattle, Washington

<u>Mussel Watch</u>:

Battelle Memorial Institute
- Battelle New England Marine Research Lab., Duxbury, Massachusetts
- Battelle Sequim Marine Research Lab., Sequim, Washington

Science Applications International Corporation, LaJolla, California
Texas A&M Research Foundation, College Station, Texas

<u>Specimen Bank</u>:

National Bureau of Standards
- Center for Analytical Chemistry, Gaithersburg, Maryland

<u>Quality Assurance</u>:

NOAA: National Marine Fisheries Service
- Northwest and Alaska Fisheries Center, Seattle, Washington

National Bureau of Standards
- Center for Analytical Chemistry, Gaithersburg, Maryland

National Research Council of Canada, Ottawa, Ontario

<u>Ship Support</u>:

NOAA: National Ocean Service; Office of Marine Operations
- Atlantic Marine Center, Norfolk, Virginia
- Pacific Marine Center, Seattle, Washington

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3. Specimen Bank
4. Test and Evaluation
5. Historical Trend Assessment
6. Quality Assurance

The first two components provide measurements of concentrations of toxic chemicals in marine organisms and sediments and of biological parameters that reflect anthropogenic stress. They are large field sampling and measurement activities, and they comprise the primary environmental data gathering activities of the NS&T Program. They will be described separately in more detail.

The other four components are complementary support projects designed to help improve and interpret the monitoring measurements. As the primary objective of this paper is to describe the monitoring being undertaken, these complementary components are only briefly summarized.

The *Specimen Bank* component (Lauenstein 1986) entails preserving samples of fish and bivalve tissues and sediments from selected sites along the coasts of the United States under liquid nitrogen temperatures (-110° to -150° Centigrade). At such temperatures, only minimal levels of chemical degradation are expected to occur over decades. Preservation of samples under these conditions will allow retrospective determinations of concentrations of newly identified contaminants and also permit retrospective analysis for contaminants using newer, more sensitive analytical techniques than are now available.

The *Test and Evaluation* component evaluates and interprets the significance of measurements that are presently included in the two monitoring projects, and develops and tests improved measurement techniques and new types of measurements to be added to these projects. Special studies of various types—often including intensified field sampling in a specific estuary or other area of particular interest—are conducted to meet these goals.

In addition to NOAA, many organizations collect data relevant to assessing the status and trends in environmental quality in US coastal waters. They include state and local environmental agencies, other Federal agencies, industrial and municipal waste dischargers, and academic institutions. The *Historical Trend Assessment* component is designed to take advantage of these data sources. Existing data are used for background information to provide an historical perspective for interpretation of data currently being obtained in the NS&T Program and for establishing trends in levels of contaminants and their bioeffects (Matta et al. 1986; Ocean Assessments Division 1986a).

The *Quality Assurance* component is included in the NS&T Program to ensure that the data obtained in the program meet rigorous criteria of consistency, accuracy, and precision. It includes specification of extensive calibration and standardization procedures for all chemical measurements. To promote compatibility of results among the several laboratories that participate in the program, regular inter-laboratory comparisons are conducted using reference materials prepared specifically for the NS&T Program. This component also includes such activities as the development of manuals containing detailed descriptions of sample collection and analysis methods and organization of periodic quality assurance workshops which bring technical specialists participating in the program together with selected outside experts to discuss ways to improve measurement procedures.

BENTHIC SURVEILLANCE

The Benthic Surveillance Project provides for measurement of the large number of chlorinated, synthetic, organic compounds; polycyclic, aromatic, hydrocarbon compounds (PAHs); and trace elements listed in Table 2. These measurements are made to determine the concentrations of these substances in bottom fish and in surficial sediments taken from the same sites. A number of additional measurements are included to provide a basis for normalizing the contaminant data and to remove some of the expected variability. These normalizing measurements include determinations of grain size of sediment, total organic carbon (TOC) content, concentrations of aluminum and silicon, and length, weight, and sex of fish.

Three other types of measurements are presently included on a trial basis in the Benthic Surveillance Project. Determinations of the frequencies of visible and histopathological lesions in bottom fish are included to allow evaluation of the validity of such measurements as indicators of biological response to toxic chemicals. Two measurements associated with sediments—those for the fecal sterol, coprostanol, and spores of the fecal bacterium, *Clostridium perfringens*—are included to evaluate their validity as indicators of contamination by domestic sewage. Additionally, measurements are carried out to determine concentrations of PAH metabolities in fish bile. These measurements are used to gauge contamination of fish by PAHs; the presence of parent compounds in fish tissue is not considered a reliable indicator of contamination because these compounds are rapidly metabolized in fish livers. Table 3 provides a summary of the types of measurements made in the Benthic

Table 2

Parameters measured as part of the National Status and Trends Program

Chlorinated Synthetic Organics	Polycyclic Aromatic Hydrocarbons	Elements	Other Parameters
Aldrin	Acenaphthene	Aluminum	Bivalve gonadal state
Alpha-chlordane	Anthracene	Antimony	Bivalve length, weight, sex
o,p'-DDD	Benz(a)anthracene	Arsenic	*Clostridium perfringens* spores
p,p'-DDD	Benzo(a)pyrene	Cadmium	Coprostanol in sediments
o,p'-DDE	Benzo(e)pyrene	Chromium	Fish external lesions
p,p'-DDE	Biphenyl	Copper	Fish histopathological lesions
o,p'-DDT	Chyrysene	Iron	Fish length, weight, sex
p,p'-DDT	Dibenz(a,h)anthracene	Lead	PAH metabolities in fish bile
Dieldrin	2,6-Dimethylnaphthalene	Manganese	Sediment grain size
Endrin	Fluoranthene	Mercury	Sediment TOC
Heptachlor	Fluorene	Nickel	
Heptachlor epoxide	1-Methylnaphthelene	Selenium	
Hexachlorobenzene	2-Methylnaphthalene	Silicon	
Lindane(gamma-BHC)	1-Methylphenanthrene	Silver	
Mirex	Naphthalene	Thallium	
Trans-nonachlor	Perylene	Tin	
Dichlorobiphenyls	Phenanthrene	Zinc	
Trichlorobiphenyls	Pyrene		
Tetrachlorobiphenyls			
Pentachlorobiphenyls			
Hexachlorobiphenyls			
Heptachlorobiphenyls			
Octachlorobiphenyls			
Nonachlorobiphenyls			

Surveillance Project. They are classified according to the sample matrix types in which they are determined.

The Benthic Surveillance measurements have been made annually at about 50 sites located along the coasts of the United States for the past three years. Sampling at these sites will be continued indefinitely to determine if long-term temporal trends

Table 3

Major types of measurements made in the Benthic Surveillance Project

	SAMPLE MATRICES				
Parameter	Sediments	Bottom Fish			
		Stomach	Liver	Bile	Other
Trace and major elements	XX	XX	XX		
PAHs	XX	XX			
PCBs	XX	XX	XX		
Other chlorinated HCs	XX	XX	XX		
PAH metabolites				XX	
Histopathology and visible lesions					XX
Food organism identification		XX			
Sewage tracers	XX				
Percent lipids		XX	XX		
Length, weight, age					XX
Grain size	XX				
TOC/carbonates	XX				

are occurring in concentrations of the toxics and other properties being measured. However, this sampling will not continue at annual intervals, but will occur less frequently as baseline concentrations and relative levels of contamination in the various areas become established. The sampling sites are located primarily near urbanized, industrial areas, but a few relatively pristine sites are included to serve as reference or control points. Within a developed estuary, bay, or other area of interest, locations are selected so that they are not within the zone of initial dilution of any point source or near any authorized dump sites. The sites are in locations which are believed to be depositional environments for sediments and contain populations of the appropriate target bottom fish.

Three stations are occupied at each site, and three separate surficial sediment samples are collected at each station. The three samples from each station are combined to form one composite sample which is preserved by freezing for later laboratory analysis. Fish are collected by otter trawl at each site; at least 30 individuals of each of two fish species are sampled. As the sampling sites are located in diverse coastal areas of the United States, it is not possible to collect fish from the same two species at all of the sites. However, only species that are known to be common and widely distributed at a site are selected to be collected from that site, and all fish sampled in the project are demersal species that consume benthic and epibenthic invertebrates. The fish are measured and examined for visible lesions immediately after collection, and various tissues are then excised and frozen for later laboratory analysis.

Special precautions are rigorously followed during all sampling procedures to minimize contamination of the sediment and fish tissue samples. For example, all fish tissues are excised in a portable, positive-pressure, laminar-flow hood using specially cleaned implements which are used to dissect only one fish before they are returned to the laboratory for cleaning. Two sets of implements are used to obtain each tissue sample. One set is used to make the initial cuts through the potentially contaminated skin or body wall of the fish in order to expose the target tissue, while a second set—including titanium knives to avoid contamination from iron or chromium—is used to excise the tissue. To further minimize contamination, sampling equipment and storage containers are composed of or coated with teflon whenever possible.

MUSSEL WATCH

The measurements made by the Mussel Watch Project are quite similar to those described for the Benthic Surveillance Project. Mussel Watch includes measurement of the concentrations in tissue and sediments of the same potentially toxic chemicals (Table 4); however, in the Mussel Watch Project toxic concentrations are measured in bivalves, not in fish. In addition, the bivalves are collected from nearshore beds so the tissue concentrations represent conditions in surface waters along the shoreline rather than in bottom waters farther from shore. As in the Benthic Surveillance Project, surficial sediments from depositional areas near each Mussel Watch station are collected and analyzed for toxic chemicals to provide longer term integrated measurements of contaminant levels.

The Mussel Watch sampling is conducted at about 150 sites along the coasts of the United States (see Ocean Assessments Division 1986b for exact locations). In order to facilitate comparisons with earlier results, 37 of the present sites coincide with locations where toxic chemical concentrations in bivalves were determined

Table 4

Major types of measurements made in the Mussel Watch Project

	SAMPLE MATRICES	
Parameters	Bivalves	Sediments
Trace and major elements	XX	XX
PAHs	XX	XX
PCBs	XX	XX
Other chlorinated HCs	XX	XX
Histopathology and visible lesions	XX	
Chemical sewage tracer	XX	
Percent lipids		XX
Gonadel index	XX	
Size and weight	XX	
Grain size		XX
TOC/carbonate		XX

as part of a national mussel watch program sponsored by the US Environmental Protection Agency from 1976 to 1978 (Goldberg et al. 1978; Farrington et al. 1983).

It has been recognized that the ability of bivalves to accumulate and retain contaminants varies with the life history and reproductive state of the animals. To minimize this variability, and especially to avoid the spawning period, all sampling is conducted during the winter.

The exact species of bivalves sampled at each site vary depending on which species are common locally. Mussels are collected on the West Coast (*Mytilus edulis* and *M.californianus*) and the northern part of the East Coast (*M.edulis*), and oysters are collected on the Gulf Coast (*Crassostrea virginica* and *Ostrea equestris*) and the southern part of the East Coast (*C.virginica*).

As in the Benthic Surveillance Project, three separate stations are established at each site. At each station about 50–80 mussels or 30–50 oysters are collected. These animals are scrubbed to remove external extraneous material from the shells and then frozen for later laboratory analysis of accumulated toxic chemicals. The procedures for collecting surficial sediment samples are the same as for Benthic Surveillance: three samples are collected at each site and then combined before freezing for laboratory analysis.

The Mussel Watch sites were sampled once in the winter of

1985–86 and will be sampled again during the winter of 1986–87. As with Benthic Surveillance, it is anticipated that Mussel Watch sampling will be conducted periodically indefinitely into the future, with varying periods of one to four years between sampling efforts.

INITIAL RESULTS

Although the Benthic Surveillance Program has been collecting samples for the past three years, laboratory measurements have been completed and resulting data subjected to preliminary analysis only for the first year (1984). For Mussel Watch, which conducted its first sampling series during the winter of 1985-86, analysis of results has just started, although laboratory measurements for the first collection period have been completed.

This section presents some examples of the preliminary results derived from the NS&T Program. Given the limited availability of analyzed data to date, the discussion must be limited to three examples of initial findings primarily from the Benthic Surveillance sampling in 1984.

One of the best ways to examine the NS&T results is to compare concentrations of a particular contaminant at various sampling locations. Figure 1 presents such a comparison for levels of total PCBs in sediments at the Benthic Surveillance sites. Sedimentary concentrations are less than 100 ng/g at most sites. However, in certain areas—especially near large cities—concentrations exceed this level, indicating substantial contamination of these sites by PCBs. The level for Boston Harbor, which is greater than 17,000 ng/g, is much higher than that for any other area sampled, indicating that this area should be examined closely for insight into potential problems associated with this contaminant.

This approach for determining relative levels of anthropogenic contamination by a potentially toxic substance is not as appropriate for certain contaminants as it is for PCBs. Some contaminants, unlike PCBs, occur naturally in the marine environment. For these substances, natural variability must be taken into consideration when attempting to evaluate levels of contamination caused by human activities.

Figure 2 illustrates that such variability can be at least partially accounted for by plotting lead concentrations against percent aluminum in sediments from 15 Benthic Surveillance sites along

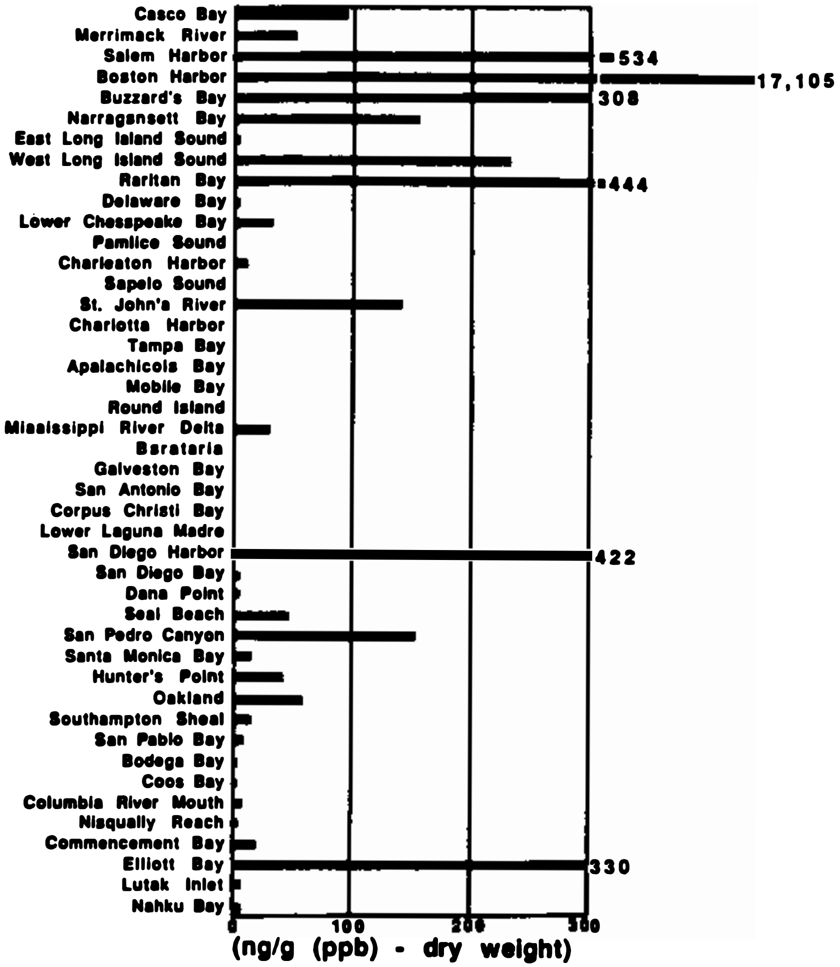

FIGURE 1 Concentrations of PCBs in sediments at Benthic Surveillance sites in 1984.

the Gulf and southeast Atlantic coasts and from 6 Mussel Watch sites in Chesapeake Bay. A similar approach has been used by Goldberg et al. (1979) to assess temporal trends of contamination in the Savannah River Estuary. In the present case most of the points fall along an approximately straight line, indicating that the ratio between the two elements follows their natural pattern of input. However, for the two sites indicated in Figure 2, the amount of lead is greatly increased compared to aluminium.

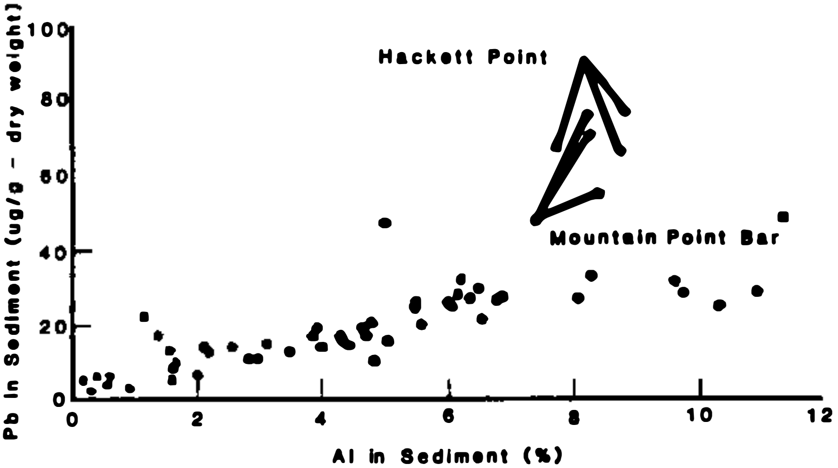

FIGURE 2 Relation of concentration of lead to percent aluminum for sediments from six Mussel Watch sites (1985–86) in Chesapeake Bay and from 15 Benthic Surveillance sites (1984) along the southeast Atlantic and Gulf coasts.

These sites, which are both in the upper Chesapeake Bay, are near major anthropogenic input sources and are areas which should receive further attention with regard to possible anthropogenic contamination by lead.

In addition to measuring levels of chemical contamination, the NS&T Program is attempting to monitor bioeffects which may be related to such contamination. For example, at six Benthic Surveillance sites along the northeastern coast of the United States the following fish disorders are of interest:

- inflammatory giant cells in the tubular epithelium of the kidney;
- inflammatory necrotizing granulomas in the kidney;
- melanin-macrophage center proliferation in the kidney;
- proliferative biliary hyperplasia in the kidney;
- hepatocellular necrosis in the liver.

The frequencies of these disorders tend to be higher in Salem and Boston Harbors than at the other sites, as these are two sites where relatively high concentrations of PCBs and presumably other contaminants occur. Although the incidence of fish disorders in these areas cannot currently be directly attributed to levels of

PCBs or any other contaminants present, this correlation indicates that priority should be given to further investigation of levels of contaminants and possible resultant bioeffects in these two harbors.

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Atmospheric Sulphur and Nitrogen Deposition and Their Impact on Acid Precipitation in the USSR

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Systematic observations of snow pack contamination levels and aerial measurements of transboundary sulphur compound transport have been underway in the USSR for approximately five years (1,2). Data yielded by these measurements have been used to evaluate the primary elements of the atmospheric sulphur balance in the USSR. These observations have been supplemented in recent years with measurements of nitrogen compounds and snow water pH values to generate a sufficiently complete, large-scale picture of both acidification and contamination of the environment.

PRIMARY ELEMENTS OF THE ATMOSPHERIC SULPHUR BALANCE

Determinations of sulphur's average residence time in the atmosphere have shown that the the atmospheric sulphur balance within the USSR is a closed system, i.e., most of the sulphur introduced into the atmosphere remains within the country's territory. The mean residence time of sulphur in the atmosphere has been assessed by airborne measurements of sulphur abundance in the air column and its deposition (3). Sulphur abundance in the air column has been established by airborne sensing at regular intervals in areas which have stations that are part of the Transboundary Air Pollution Monitoring System. These stations monitor sulphur deposition under the EMEP program. In addition, winter sulphur deposition was assessed using data obtained from a snowpack pollution study. Sensing of the atmosphere was conducted at a height of three to five kilometers. The bulk of sulphur dioxide is usually transported within a distance of 1.5 kilometers, and sulfates are transported up to three kilometers (2). Reliable values for the average residence time of sulphur in the atmosphere ranged from 3.1 to 5.1 days for different regions. The average value was close to four days.

Internal factors account for a relatively small portion of total sulphur emissions: the territorial dimensions of the USSR, transport rates in the lower troposphere (customarily hundreds of kilometers a day), the prevailing west-to-east air mass flow, and the fact that the primary release points of sulphur emissions are in the European portion of the USSR at a considerable distance from the border. An additional factor is the mean, established residence time of sulphur in the atmosphere. With annual sulphur deposition in the continental USSR at 13.3 million tons, there should be an average of approximately 0.15 million tons of sulphur in the atmosphere over this area.

Analysis has shown that we can ascertain the main sources and sinks for anthropogenic and natural atmospheric sulphur. Bearing in mind that a virtual equilibrium exists between the mean annual input of sulphur into the atmosphere in the USSR and its sink, we can formulate the following correlation (4):

$$q_{ant} + q_{tr} + q_{soil} + q_b = A_k + A_{ck} + A_m + Q^3_{tr} + Q^{S+E}_{tr} + Q_{u.tr}$$

where q_{ant} is anthropogenic sulphur emissions into the atmosphere; q_{tr} is the cross-border flux of sulphur over the western border of the USSR; q_{soil} is particulate from saline soils in arid zones of Central Asia; q_b denotes the contribution from eolian weathering of rock and from the upper troposphere which determine background pollution of broad areas; A_k represents deposition over the continental USSR; A_{ck} is deposition for the Northern Arctic Ocean; A_m denotes deposition in enclosed seas (Aral, Caspian, and Black); Q_{tr} is flux across the western border; Q^{S+E}_{tr} represents flux across the eastern and southern borders; and $Q_{u.tr}$ is transport to the upper troposphere.

Table 1 lists the findings from our assessment of the main elements in the atmospheric sulphur balance. Man-made emissions (q_{ant}) within the USSR are taken from official statistics provided by EMEP on sulphur dioxide emissions (5). Sulphur transport to the Soviet Union across its western border (q_{tr}) and the flux back across this boundary (Q^{S}_{tr}) were determined by aerial measurements. Sulphur contribution from saline soil particulates (q_{soil}) was calculated from snowpack pollution measurements in areas north of the Caspian and Aral Seas. This is clearly only a fraction of the sulphur resulting from the intense process of eolian transport observed in Central Asia. However, particulate diffusion here is essentially a local phenomenon and therefore does not upset the overall balance in the country. The sulphur contribution from the upper troposphere and eolian weathering of rock in the country's northern regions (q_b) was calculated from minimal sulphur concentration values in the snow of the northern and central areas of the easternmost half of Soviet Asia (remote from anthropogenic sources). These concentrations total on the average 0.3 mg/l, which is consistent with an annual deposition of 1.1 million tons. The values for A_k, A_{ck}, and A_m were determined from snowpack pollution. These figures were recalculated for snowless periods using data on sulphur deposition from the year-round network of stations which monitor the chemical composition of precipitation (1).

Transport values from the USSR across the southern and eastern boundaries (Q^{S+E}_{tr}) were derived entirely from calculations of sulphur dioxide emissions. Transport into the upper troposphere ($Q_{u.tr}$) was determined from deposition from the upper portion of the troposphere (calculated from sulfate altitude distribution figures). This value equaled 0.5 million tons per year. Therefore, eolian weathering of rock accounts for the difference $q_b - Q_{u.tr} =$ 0.6 million tons of sulphur per year. This is a completely realistic figure, considering the large areas of exposed rock on the daytime surface and the significant areas which make up the mountain systems in the northeastern region of the USSR.

The discrepancy between the amount of sulphur input into the atmosphere and its removal is 11 percent (Table 1). This value is much lower than the errors seen for distinct elements of the balance. These findings point to a number of features which are characteristic of the atmospheric sulphur balance of the USSR.

Table 1

Elements of the atmospheric balance of sulphur in the USSR

Balance Elements	Quantity of Sulphur (million tons/year)	Quantity of Sulphur (% from sources)
<u>Sources of Atmospheric Sulphur</u>		
Anthropogenic emissions	11.8	66
Transboundary transport	4.0	22
Particulate from saline soils	1.0	6
Background (e.g., weathering, contribution from upper troposphere)	1.1	6
TOTAL:	17.9	100
<u>Sulphur Removal</u>		
Deposition in continental USSR	13.3	74
Deposition in northern Arctic ocean	0.3	2
North of 80°	0.01	--
Deposition in Caspian, Aral, and Black Seas	1.1	6
Transport across western border	0.6	3
Transport across eastern and southern borders	0.2	1
Transport into upper troposphere	0.5	3
TOTAL:	16.0	89

- Approximately 90 percent of the balance is attributable to anthropogenic sulphur emissions. The most aggressive sulphur compounds in the atmosphere are associated with anthropogenic sources: sulphur dioxide and sulfuric acid. As saline soils in the country's southern regions form particulate, gypsum particles primarily enter the atmosphere; as they display virtually no chemical activity, they have little impact on acidification of the environment.
- The balance depends to a large degree on transboundary transport, primarily across the western border. The flux of sulphur across this boundary into the USSR accounts for more than 30 percent of anthropogenic emissions. This contribution

is significantly higher in the western part of the USSR. Deposition from transboundary transport in the European portion of the USSR (an area which is delineated in the east by a line running from the Kola Peninsula along the Volga) totals 60 percent of emissions from the USSR's own release points.

- Approximately 75 percent of the sulphur entering the atmosphere over the USSR from man-made and natural sources is deposited in the continental USSR.
- Less than 0.06 percent of the sulphur entering the atmosphere is transported to the upper latitudes of the Arctic (north of 80°). The fate of sulphur compounds deposited within the USSR is to a large extent dependent upon the season. Sulphur deposited in snowless periods is primarily retained in soils. Sulphur which is deposited during the winter is washed into rivers by snowmelt runoff. About 10 percent of the sulphur in the European USSR is released into rivers by this pathway.

CONTAMINATION FROM NITROGEN COMPOUNDS IN THE USSR

Table 2 lists data on nitrate deposition in the USSR for 1985. Sulfate deposition figures are also cited here for the sake of comparison. Total sulfate deposition on land for 1985 (14 million tons per year) differs little from the average value cited in Table 1 (13.3 million tons per year). The deposition rate for man-made sulfates was derived by subtracting the amount contributed from soil erosion and eolian weathering of rock from the total deposition value.

The following method was used to determine separate deposition rates for anthropogenic and natural nitrates. Using the data in Table 2 on the deposition rate of anthropogenic sulfates $U^a(s)\,ETC$ and $U^a(s)\,ATC$ for the European and Asian portions of the USSR and total (anthropogenic and natural background) nitrate depositions for these same areas, we have:

$$\frac{U^a(s)ETC}{U^a(N)ETC + U^b(N)ETC} = 4.3$$

$$\frac{U^a(s)ATC}{U^a(N)ATC + U^b(N)ATC} = 2.5$$

where b denotes natural background deposition.

Table 2

Characteristics of mean annual sulfate deposition for 1981-85 and nitrates for 1985

Parameters	**European USSR**		**Asian USSR**		**Entire USSR**	
	SO_4(S)	**NO_3(N)**	**SO_4(S)**	**NO_3(N)**	**SO_4(S)**	**NO_3(N)**
Concentration (milligrams/liter)	1.85	0.70	0.84	0.36	1.11	0.42
Deposition rate (tons/k^2/year)	1.0	0.22	0.39	0.13	0.54	0.15
Human-induced deposition rate (tons/k^2/year)	0.95	0.14	0.32	0.046	0.47	0.069
Total land surface deposition, including cities (million tons/year)	6.3	1.6	7.5	2.5	13.8	4.1

Let us make two assumptions: (1) deposition rates for anthropogenic nitrates to sulfates in the European and Asian parts of the USSR are proportionally constant; and (2) natural background deposition is uniform for the entire territory of the USSR. We then find that $U^b(N) = 0.084$ tons per square kilometer per year, and the ratio is 0:15.

The values $U^b(N)$ may be further evaluated using a number of independent sources. An analysis of data obtained from measurements made by the Background Atmospheric Pollution Monitoring Network (BAPMoN) carried out by WMO and UNEP demonstrates that the rate of nitrogen land-surface deposition in the form of nitrates in background continental areas totals approximately 0.098 tons per square kilometer per year. Estimates of global nitrogen oxide balances in the atmosphere from manmade and natural resources give us an approximate value for deposition rates (7,8). The principal natural sources of nitrogen oxide input into the troposphere are microbiological process in soils, lightning, ammonia oxidation, stratospheric contribution, and biochemical and other reactions in the ocean. If we postulate that 90 percent of the nitrogen contributed from soils and ammonia oxidation is deposited on land surfaces, and that fluxes from lightning and the stratosphere are roughly equal over the earth's surface, then the rate of nitrogen deposition with nitrates as calculated in study (7) is equal to 0.062 tons per square kilometer per year. If we use the formula in study (8), this figure would total 0.095 (km^2/yr).

The ratios between background deposition rates for the USSR, the BAPMoN network, and the calculated values from studies (7) and (8) are therefore 1.0 : 1.2 : 0.74 : 1.1. We can then postulate that the background deposition rate we have derived for the USSR is indeed a function of natural nitrate sources. Consequently, we can tentatively conclude that for the European USSR the ratio between man-induced and natural nitrate deposition is approximately 2:1; for the Asian USSR this ratio is 1:2. A more exact figure for anthropogenic nitrates is 62 percent and 36 percent, respectively.

POSSIBLE ECOLOGICAL CONSEQUENCES OF POLLUTION OF THE ENVIRONMENT FROM SULPHUR AND NITROGEN COMPOUNDS

The environmental impact of sulphur and nitrogen compounds which are deposited in the USSR is highly diverse. There are two reasons for this: the significant prevalance of sulfate versus nitrate deposition and differing ecosystem utilization of sulphur and nitrogen.

With data on sulphur and nitrogen deposition in the USSR we can evaluate potential acidification of the environment, particularly the upper range of acid precipitation (minimal pH value) (4). It is known that where neutralization processes are absent, the majority of anthropogenic sulphur and nitrogen emissions (released as sulphur dioxide and nitrogen oxides) must be present and removed from the atmosphere in the form of sulfuric and nitric acid (5). Natural sulfates are fully neutralized and do not negatively impact the environment. The average level of atmospheric precipitation for the USSR totals 515 millimeters per year. If 20 percent of the sulphur and nitrogen is removed as dry deposition, then the average concentration of hydrogen ions deposited with precipitation and associated with sulfuric acid must total .055 milligrams per liter. The amount formed by nitric acid would total .018 milligrams per liter. Therefore, the contribution of sulfuric acid to the concentration of hydrogen ions in precipitation equals 25 percent, while anthropogenic nitric acid is only 11 percent, an insignificant amount. In Sweden, by comparison, this value is equal to 30 percent (9).

Factoring in carbon dioxide which is dissolved in precipitation, the concentration of hydrogen ions associated with sulfuric and nitric acid is .073 milligrams per liter. We then yield a pH value of 4.14. This value is typical for significant acidification of atmospheric precipitation. Where pH is a function of sulfuric acid alone, this value is 4.24. Consequently, the presence of nitrates does little to change the acidity index (pH) that is determined by sulfates.

Acid precipitation has essentially been observed in the USSR only in areas adjacent to the western border; at the regional level in the rest of the country it is generally absent (1). As analysis of the chemical composition of precipitation has demonstrated, this absence of acidification in the rest of the country can be ascribed to the anion and cation balance (10). The ion balance is coupled with the composition of anthropogenic emissions and alkaline metal introduction into the atmosphere through natural processes. This finding indicates that the ion balance—not the absolute concentration of sulfates and nitrates—plays the principal role in acidification. This ion balance must be preserved in those cases where it is not possible to reduce sulphur emissions.

Neutralizing sulfuric acid in the atmosphere and in deposition in the USSR may create the incorrect impression that there are absolutely no negative ecological consequences emanating from man-induced acidification of the environment. This is not the case. A significant portion of soils in the USSR (podzol, in particular) has high natural acidity that reduces its fertility.

In order to increase productivity, the acidity of such soils is reduced by lime treatment. More than 10 million tons of lime are used annually in lime treatment of soil, although we fall far short of meeting the demand for such treatment. It can be shown that a considerably greater portion of anthropogenic and natural neutralizers is expended in the atmospheric processes of sulfuric acid neutralization than in lime treatment. As Table 2 illustrates, the bulk of neutralized sulfates is equal to a value on the order of 10 million tons per year. The quantity of neutralizers in terms of lime is equivalent to 22 million tons, approximately two times greater than the annual amount of lime input into the soil. Where there is no anthropogenic sulfuric acid in the atmosphere, these elements would be deposited on the soils and would neutralize their natural acidity. Correspondingly, there would be less of a need to treat acidic soils with lime.

Approximately four million tons of sulphur per year in the form of sulphur dioxide and sulfates flow across the western border of the USSR from the other European nations. Most of the SO_2 and sulfates are only slightly neutralized. As the calculations in reference (5) indicate, the deposition of a portion of these sulfates on agricultural lands which are lime treated results in annual losses of roughly 1.5 million tons of industrial lime. The losses in terms of lime itself stand at 40 million rubles per year, while additional losses are incurred due to the two- to three-fold reduction in the harvest.

The ecological repercussions of nitrate deposition differ significantly from those caused by sulfates. Nitrates in the USSR have virtually no impact on acid precipitation. They are primarily deposited as saltpeter and therefore essentially serve as a nitrogen fertilizer. The average value for human-induced nitrate deposition in the European USSR in units of nitrogen is equal to 0.14 tons per square kilometer per year; for the USSR at large it is two times lower. The recommended standard for annual input of nitrogen fertilizers in the USSR—from which there are no concomitant, long-range, negative effects—is approximately 4.6 tons per square kilometer per year, i.e., thirty-fold greater than the average observed in deposition (2). This ratio reaches nearly two orders of magnitude for anthropogenic nitrates. The value of deposition does not, in effect, exceed 0.6–0.8 tons per square kilometer per year even in industrial regions. We would point out that the permissible load for forest ecosystems is usually equal to 3–4 tons per square kilometer per year. It drops to one ton per square kilometer per year for the highly sensitive northern ecosystems, while the usual standard for nitrogen input into the forests of Sweden is approximately 1.5 tons per square kilometer per year (9).

CONCLUSIONS

- Approximately 90 percent of the atmospheric sulphur balance in the USSR is attributable to anthropogenic emissions. The balance is a closed system and approximately 75 percent of the sulphur deposited in the continental USSR is from domestic release points. More than 30 percent of the anthropogenic sulphur flows across the western border of the USSR.
- The contribution of anthropogenic nitrogen to nitrate deposition in the USSR is relatively small. For the entire country, anthropogenic sources contribute 48 percent: 62 percent falls

on the European portion and 36 percent on the Asian portion. This is close to the value for the natural input of nitrates.

- Potential acidification in the USSR from sulfuric and nitric acids is characterized by a pH level of 4.14. Due to the neutralization process where there is an approximate balance between ions and cations, little precipitation acidification has been observed for most of the country. Regional-level acidification has been detected primarily in regions adjacent to the western border of the USSR which are subjected to approximately four million tons of sulphur per year in the form of sulphur dioxide and very slightly neutralized sulfates. The contribution of nitrates to acidfication in the USSR (based on hydrogen ion concentration) does not exceed 25 percent. Anthropogenic nitrates contribute roughly 11 percent.
- The mean deposition level of nitrates of anthropogenic origin totals 0.07 tons per square kilometer per year, or one and one-half orders of magnitude lower than the recommended, long-term, ecologically sound standard set for the use of nitrogen fertilizers and the permissible load for forest ecosystems.

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Testing and Evaluation of a Regional Acid Deposition Model

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The problem of acid deposition has been a major policy issue in the United States and in Europe since the mid-1970s. At that time, many scientific studies were carried out to explain the link between emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_x) and the acidic water in lakes and streams. The process was found to be rather complex. It involved the emission of the precursor SO_2 and NO_x gases; their oxidation and transport in the atmosphere; their deposition in dry or wet form; their contact with vegetation and soils; and their ultimate contribution to high acidity in waters.

This theoretical model of the cause and effect of acid deposition is now well accepted. The principal oxidation reactions in the gaseous and aqueous phases are known. The long-range transport processes have been demonstrated, and the mechanisms of watershed acidification have been identified and tested under limited laboratory and field conditions. The major scientific and research problems which have served to complicate the issue have arisen in the attempt to apply this theory to real-world conditions.

The source/receptor problem is a prime example of this dilemma. In the early 1980s it was concluded that certain lakes in the northeastern United States were acidic ($pH < 5.0$), and the scientifically acceptable explanation was that acid deposition was the cause. Clearly, however, the acidification was not the result of local source emissions within 50 miles of the receptors, as no such sources existed. The ambient particulate and gas concentrations of sulfates and sulphur dioxide were so low that it was estimated that at least one-half of the total sulfate deposition had to occur as the result of wet deposition. Meteorological back trajectories indicated that the sources of air masses associated with rainfall tended to be areas to the west of the areas with acidic lakes, but there were exceptions to this trend: acid deposition also occurred when back trajectories identified other areas as the source of the air masses.

As understanding of the problem developed, a major scientific question of concern to policy makers was the relationship between emissions and the location and magnitude of deposition. If acid deposition and particularly wet deposition of acidic materials was causing a problem in particular receptor areas of the northeastern United States and Canada, what would be the most cost-effective way to reduce levels of emissions in order to achieve reductions of deposition in these areas?

MODEL DEVELOPMENT AND MODEL PERFORMANCE EXPERIENCES

US-Canadian Assessments

Atmospheric chemistry and transport were critical in solving the acid deposition puzzle. In the early 1970s, modelers had already developed the first quantitative analyses of the long-range transport of sulphur in Europe (1). By 1980, many models existed to describe the relationship between emissions of SO_2 and long-range transport and deposition. On August 5, 1980, the United States and Canada signed a "Memorandum of Intent (MOI) on Transboundary Air Pollution," which was devoted primarily to the problem of acid deposition. To provide an adequate technical and scientific basis for the formulation of this agreement, bilateral working groups were established to prepare reports on the state-of-the-art of scientific knowledge regarding specific aspects of the problem. One working group addressed questions of atmospheric science and modeling. The major accomplishments of this group were:

- The documentation, evaluation, and intercomparison of eight regional scale models for the North American continent; and

- Assessment of the methods and assumptions of the models to quantify source/receptor relationships on an annual average (1).

As part of its evaluation, the group used available data in an attempt to test model performance. The eight models selected for evaluation and comparison represented the complete range of available models. All of the models were "linear" in that chemical transformations and scavenging were expressed as first order processes with rate constants independent of rates of emissions and co-pollutant concentrations.

Each model was able to simulate transport, dispersion, transformation, and deposition of sulphur compounds for eastern North America, but they differed significantly in many important ways. For example, the scale of grid cells for source emissions varied from 70 to 190 km. The model types included Lagrangian box, statistical trajectory, Monte Carlo simulation, and puff trajectories.

Evaluation Criteria

The working group adopted a simple, conventional set of criteria for evaluating performance using differences between observed measurements (C_o) and model predicted values (C_p) for monthly and annual average ambient sulfate concentrations and wet sulphur deposition. Two measures related to the differences between these values were calculated. First, the average error where:

$$\bar{\epsilon} = \sum_{i=1}^{n} \frac{(C_{pi} - C_{oi})}{n} \qquad \{1\}$$

where i is the number of observations at a site and the standard deviation of that error σ_e

$$\sigma_e = \sum_{i} \frac{(C_{pi} - \sum_i C_{oi}/n)^2}{n-1} \qquad \{2\}$$

If a model performed well, it was expected that $\bar{\epsilon}$ should be close to zero. Further, σ_e should be small, indicating that the scatter of the model predictions is small.

Another criterion used by the working group was based on the relation of observed and predicted values, i.e., C_{oi} and C_{pi}. The average value of the relation of these measurements was defined as

$$M_g = \sqrt{\prod_{i=1,\ldots,n}^{n} \frac{C_{oi}}{C_{pi}}} \qquad \{3\}$$

where $i = 1$, n is the number of observed measurements at a site which is the geometric mean of the ratio value. Also, S_g can be computed as the standard deviation of M_g. For an ideal model, both M_g and S_g should be close to unity.

Finally, it was assumed that a valid model should generate errors between predictions and observations which are randomly distributed, i.e., the errors should not be correlated with the magnitude of the predictions. The criterion was that the cross correlation between e and C_p should be small.

$$\rho_{e}, Cp \ll 1.0 \qquad \{4\}$$

Model Evaluation Failure

At the time the evaluation was attempted, the evaluation data set contained only eight points for annual wet sulphur deposition and nine points for annual sulfate concentrations. Data for seasonal evaluation were limited to observations during the months of January and June 1978. The available data points turned out to be insufficient in number to make statistically significant comparisons with respect to model performance. Although a good start was achieved by developing a set of acceptable criteria for evaluation, further testing had to await the availability of additional air quality and deposition data.

Model Diagnostics

An acceptable model must be able to predict air quality and deposition associated with a given level and pattern of emissions. However, all models are developed with liberal use of calibration in order to improve their fit with available data in explaining the source/receptor relationship. Typically, models such as those compared in the US-Canada activity have been developed and calibrated using the same limited emission and air quality and deposition data. These available data are fairly recent, but there has been no way to subject the models to the truly important test:

to determine their ability to adequately predict air quality and deposition levels resulting from a major change in present emissions, such as a shift in geographical distribution or a reduction in overall levels.

The ideal way to test such models would be to observe their performance under such major changes. Another less satisfactory but nevertheless helpful way to address this question is to examine whether the models appear to be predicting the results for the correct reasons.

This question can be addressed both empirically and theoretically. The empirical approach is possible only if extensive field data are available on actual transport of air masses, real-time rates of conversion of SO_2 to sulfates, wet scavenging rates, and dry deposition rates. Each of the models compared in the MOI effort simulated these processes by some form of parameterization. In the early 1980s data on wet deposition were insufficient to make even statistical evaluations of performance among models, precluding the possibility of trying to determine whether they were working for the correct reasons.

The few data that were available, however, did indicate a disturbing problem. While the models appeared to be able to predict annual average wet deposition with some accuracy, they produced seasonal estimates of wet deposition that were widely different from observed values. However, owing to the small amount of data used to generate both the seasonal and the annual average deposition measurements, these results were ambiguous. With more predictions and observations, the averages might converge. Only if such differences were to appear in a much more robust set of observations could one conclude that the models were giving the correct predictions for annual average deposition for the wrong reasons, e.g., compensating errors.

The theoretical approach also failed in the MOI comparison and evaluation. All of the models reviewed were highly parameterized and simplified versions of real-world physical and chemical processes involved in the acid deposition phenomenon. In spite of the fact that they were all developed by a fairly small group of specialists in the atmospheric sciences, they nevertheless displayed substantial diversity in structure and techniques used to represent processes.

An example of this diversity is the models' treatment of transport and dispersion. One model applied a statistical approach to simulate sulphur concentrations and deposition on an annual basis while others attempted to compute trajectories generated from available wind field data on a monthly or more frequent time period. Their treatment of wind field data also varied considerably. For example, each of the models defined effective transport wind differently. Some assumed it to be the surface wind, others assumed it to be at a height near 1,500 meters, while still others assumed it to be a mixed layer average wind. These diverse approaches led to quite different applications of available upper level wind measurements (400 km spacing) and surface wind measurements (150 km spacing). Similar differences existed in the models' treatment of emission sources, conversion chemistry, and scavenging for wet deposition.

The problem was that all of the approaches represented reasonable simplifications and parameterizations consistent with theory. Without detailed field data on actual mechanisms and processes, it was impossible to conclude on the basis of theory or state-of-the-art scientific knowledge that one representation was better than another.

Application of Models

Even though the available data on air quality and deposition were inadequate to evaluate or absolutely compare model performance, the working group did apply the models to a hypothetical problem to test their relative performance in prediction. Using meteorological data for 1978, the group ran each model to generate a matrix of transfer coefficients to relate emissions of sulphur from 11 source regions in the United States and Canada to nine selected receptor regions. The linear character of the models made this approach acceptable. The transfer matrix coefficients for any model k comprise an 11 × 8 matrix

$$[T_{ijk}]i = 1, \ldots, 11, j = 1, \ldots, 8 \tag{5}$$

where T_{ijk} represents the amount of sulphur that is deposited over a year at receptor area j, owing to a unit level of annual emissions of sulphur from source region i, and predicted by model k.

As a result of these applications, the group found significant differences among the T_{ijk} values, i.e.,

$$T_{ijk} = /T_{ijk+1} \tag{6}$$

These differences would result in substantially different predictions about the effect of emissions reduction upon deposition in receptor areas. The differences were so great that they presented irreconcilable conflicts in attempting to choose one emissions reduction strategy over another in order to achieve any particular target loading objective.

Conclusions of the Evaluation

The results of the MOI evaluation were not comforting either to scientists or to policy makers. Available models appeared able to predict existing patterns of annual average wet sulphur deposition. However, this conclusion was considered to be very weak due to the sparse data available for performance evaluation and to the fact that all of the models were calibrated using either the same emissions and deposition data or data of comparable magnitude. When applied to scenarios of emissions reductions, the models provided predictions of reductions in deposition in receptor areas that varied so greatly that they were of questionable value for policy making.

DEVELOPMENT OF THE REGIONAL ACID DEPOSITION MODEL

The MOI experience revealed major shortcomings in the state-of-the-art of regional atmospheric models. Three of the most glaring weaknesses shared by all models were:

- The lack of realistic chemistry submodules;
- The overly simplistic nature of horizontal transport (one- or two-layer models); and
- The inability to predict the effects of episodes.

Scientific knowledge had progressed to the point where these processes were believed to be the most important in addressing the acid deposition phenomenon, yet they were not adequately treated in the models.

There are many examples of the poor fit between the models' representation and the real world. Field study results indicated that aqueous phase conversion of SO_2 to sulfate (estimated to be the dominant oxidation mechanism) might be nonlinear owing to oxidants, and in particular H_2O_2, as limiting factors. Figure 1

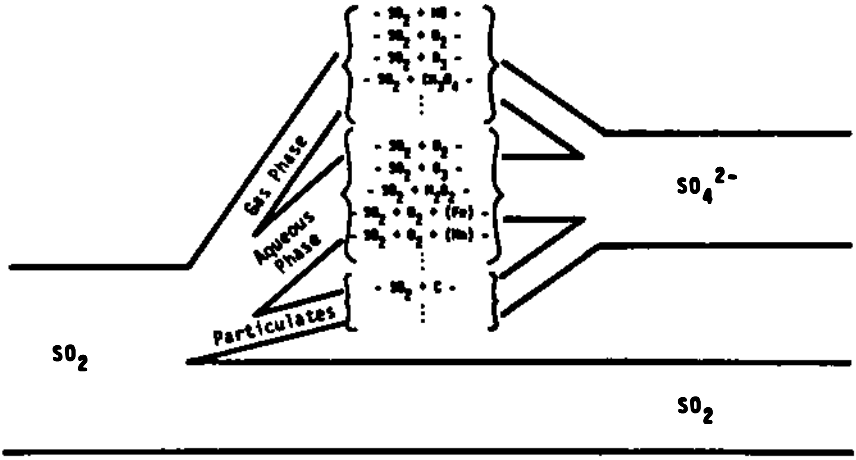

FIGURE 1 Sample processes in SO_2 oxidation.

provides a simple, conceptual, algebraic formulation of a possible situation where a reduction in SO_2 emissions might result in a nonlinear response.

Similarly, plume studies showed great differences in diurnal transport. Venting of tall stack emissions above the lowered boundary layer at night caused rapid, concentrated transport of plumes before re-entrainment in the mixed layer.

Finally, wet deposition data were collected that indicated that the majority of sulfate deposition during a year could be associated with very few rainfall events. Understanding the chemistry and transport of these episodes, therefore, seemed crucial in clarifying some of the uncertainties inherent in the more simplistic models. In addition, the existing models differed significantly in their treatment of scavenging, aggregation of emissions, and rate parameters assumed for important chemical and physical processes. Many of these differences could be explained by the independent origins of the models. Individual researchers often developed models with quite different objectives in mind, leading to differences in structure and/or process which might not have occurred had there been a coordinated effort to produce an optimal model of regional source/receptor relations for acid deposition on a regional scale.

The MOI performance evaluations showed wide divergence among the predictions of the various models. Yet observation data on air chemistry and wet deposition were far too few to determine that these variations were statistically significant, given the inherent variation in the annual average observations of these measures. Moreover, the application of the models to derive transfer matrices relating source regions to receptor regions would produce results so diverse that they would substantially complicate formation of a coherent policy intended to reduce emissions by reducing deposition in targeted sensitive receptor regions.

In 1982 the US Environmental Protection Agency (EPA), in coordination with other federal agencies, began the development of a new Regional Acid Deposition Model (RADM) through the National Center for Atmospheric Research (NCAR) at Boulder, Colorado. The purpose of the research effort was to develop a state-of-the-art regional model. The model was to be Eulerian in structure and capable of incorporating in its submodules the latest scientific knowledge concerning transport, chemistry, and deposition. A decision was made at the outset that to achieve these aims the model would have to operate on a spatial and temporal frame rich enough to capture the influence of episodes.

The RADM is now complete. It has been run using available data sets and refined so that it is ready for application. The model's chemistry is very complex, however, so that the approximate running time on a computer is one-tenth hour for every hour of simulated real time. The only submodule of the model that may need revision to reflect properly the state-of-the-art is the wet scavenging module. Estimates are that revision of this module could reduce the ratio of computer processing time to simulated time by as much as a factor of 10.

It is reasonable to question the utility of a tool which is so complex and expensive to use, but RADM has two extremely important uses. The first is scientific. The model incorporates into its numerical simulation the best of current knowledge, and it can be run to test the sensitivity of its many components to different assumptions such as values of rate constants. These sensitivity runs can also help prioritize research needs based on the extent to which particular uncertainties contribute to differences in model predictions.

The second important use of RADM is to analyze the effects of emissions reductions on the pattern and magnitude of acid deposition. A simplified engineering version of RADM is being developed which will allow operation at a much lower cost to explore multiple emissions control scenarios.

MODEL EVALUATION

Models of complex phenomena abound in the field of environmental sciences. However, the number of models which have been tested and evaluated effectively against real world data is very small. To some extent, RADM and other such models have partial testing and evaluation built into their construction. Submodules are constructed based on theory that has usually been verified in the laboratory or by limited field study. To the extent that RADM incorporates state-of-the-art knowledge in its submodules, it has passed the test of scientific acceptance as one of the best approaches developed to date in addressing the source/receptor problem.

The use of models for policy analysis, however, demands a higher standard of evaluation. With regard to RADM, two additional measures of performance have been established for testing:

- Does the model make predictions that are consistent with field observations?
- Does the model perform well against observations for the correct reasons?

The necessity of the first criterion is self-evident; the second is necessary because of the under-determination of the modeled system. Parameters can be adjusted to achieve a good fit between predictions and observations to the extent that RADM could work because of many compensating errors.

Operational Performance Criteria

The MOI evaluations relied primarily on comparison of statistics on model predictions and observations, e.g., means, standard deviations, and differences. This approach has several limitations in trying to design a practical field test for a model like RADM:

- Monitoring data on air quality and deposition will be point data, whereas model predictions will be averaged over an 80 km grid cell.
- Distributional statistics (e.g., means, variances) may not reveal the spatial characteristics of data. Two markedly different fields can have the same distributional properties.

Given the limited amount of available resources to test and evaluate the model, a decision was made to seek a cost-effective way to deal with the spatial aspects of performance as well as the more conventional statistical comparisons.

The primary objective of the operational test and evaluation of the model is to gather monitoring data on atmospheric chemistry and wet deposition at a sufficient number of sites and with sufficient frequency to determine whether the model fails to predict seasonal and annual average values for air quality and deposition with an accuracy of 30 percent or less. This objective dictated the number of sites required because density of monitoring sites determined the measurement error inherent in the network itself, owing to expected spatial variation and the limited coverage of the point network.

Kriging

The need for design of a technically and economically feasible field test of model operation has led to the choice of a "bottom line," pattern-based, point-to-point comparison for model predictions versus observations. The core of the approach is the application of a geostatistical tool called *Kriging* to generate patterns of predicted seasonal and annual air quality and deposition which are compared to similar patterns derived from monitoring observations.

Kriging provided a way to deal quantitatively with the comparison of the smoothed patterns of model predictions (averages over 80 km grid cells) versus the point data from monitoring sites. As an interpolation technique, it is attractive because it can preserve the main characteristics of the data by smoothing through random variability. Kriging is not unduly influenced by single points but retains important spatial features and provides a quantitative means to represent uncertainty in interpolation estimates which are produced.

Kriging is based on a theory of regionalized variables designed to mathematically describe phenomena distributed in space and/or time and provides an appropriate means for solving spatial estimation problems. It departs from traditional deterministic interpolation methods in that the interpolation weights depend on the covariance structure of the regionalized variable. The mathematical details of the procedure can be found in reference 2.

For purposes of model testing and evaluation, it is more important to know that application of the technique allows for construction of a confidence interval for the difference in observed and predicted values as follows:

$$Y_p - Y_o \pm 1.96[\mathrm{Var}(Y_p) + \mathrm{Var}(Y_o)]^{1/2} \qquad \{7\}$$

where

$Y_p =$ Kriging estimate for the model prediction at the Kriging grid mode
$Y_o =$ Kriging estimate for the observed data at the grid mode
Var = Kriging variance estimate

If the deviations of Kriged values from true values have a normal distribution, this is a 95 percent confidence interval. The confidence interval can serve as the basis for determining the expected power of a given density of observed monitoring data which in turn determines the relative accuracy with which a model can predict air quality and deposition data.

Field testing and evaluation of the RADM model will focus primarily on the objective of collecting sufficient surface monitoring data to allow rejection of the model if it fails to predict within ± 30 percent the seasonal average air quality and wet deposition observations as calculated by the Kriging calculation in equation 7.

From what is known presently about measurement error inherent in monitoring methods and local spatial variability in measures of interest, it is estimated that approximately 70 monitoring stations will be required to gather data during a one-year period over the eastern United States and Canada to obtain enough statistical evidence to determine whether the model is achieving ± 30 percent accuracy for seasonal averages.

The US Government is proposing to carry out this evaluation program jointly with the Government of Canada and the privately funded Electric Power Research Institute (EPRI) based in Palo Alto, California. The program assumes two years of monitoring data are necessary because the first year's data will be needed to fully calibrate the model, which has not been possible to date due to lack of data.

Diagnostic Evaluation

It is unlikely that emissions over the study period will vary sufficiently to assume that the operational evaluation will observe performance over a significant range of seasonal emissions levels. It is also unlikely that such influences could be sorted solely on the basis of meteorologic variation during the study period.

However, it appears likely that the operational evaluation will determine whether the model worked in predicting regional air quality and acid deposition associated with a known pattern of emissions. It is less likely that this conclusion can be extrapolated to emissions patterns significantly different from those in the study.

As part of the planning for model evaluation, two possible ways to overcome this serious deficiency were examined. The first method to be considered was a major source modulation made possible by temporary fuel switching, e.g., from coal to natural gas in firing a number of major utility boilers. This option was rejected because the cost of a reduction of sufficient magnitude and duration was estimated to be in excess of $750 million.

The second option was to use a reactive tracer such as S_{34} or S_{35} to tag emissions, thereby allowing direct testing of model processes. The former tracer was rejected because of the quantity required and the associated costs necessary to provide an adequate signal to background noise; the latter was rejected because of its radioactive characteristics.

At the present stage of planning, a series of intensive field studies called "diagnostic studies" are being considered to complement the operational monitoring program. These studies are designed to provide measurements such as vertical profiles of air chemistry, transport, and wet deposition as a means of verifying that the processes are working according to the model. If these mechanisms are not reasonably consistent with model operations, it can be concluded that the model is working for the wrong reasons.

Detailed proposals for such diagnostic studies are currently being prepared. Their design is proving to be most difficult. As was the case for the operational test and evaluation, quantitative goals that make sense scientifically must be specified. It is unlikely that tests as rigorous as those used for the operational evaluation will be able to be applied. However, before conducting these studies it is necessary to specify which measurements need to be made, on what temporal and spatial scale they will be made, and how they will be used in quantifying model performance. Detailed planning is scheduled for completion in early 1987.

EPA has developed a new generation regional and deposition model. A design for an air quality and deposition monitoring network that will operate for two years has been prepared. The design includes an innovative geostatistical approach that allows the discriminating power of the performance evaluation test to be estimated in advance. The operational field program is scheduled to begin in late 1987.

In addition, EPA is presently preparing detailed plans for short-term, intensive diagnostic field studies to supplement the surface monitoring network and to test whether the model actually describes mechanisms as they occur. Those plans are scheduled for peer review and approval or rejection in 1987.

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Climate Predictions, Regions, and Resources

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CLIMATE PREDICTIONS AND RESOURCE ANALYSES

Increasing atmospheric concentrations of carbon dioxide (CO_2) and the resulting climate changes can affect renewable and nonrenewable resources such as ecosystems, forestry, agriculture, water, fisheries, human populations, and energy supplies. To anticipate the consequences of these CO_2-climate interactions, it is necessary to integrate predictions of future climate conditions with resource data.

Modeling the effects of increasing atmospheric carbon dioxide on climate has been moving from global and hemispheric scales toward finer geographic resolution. General circulation models (GCMs) of the atmosphere are the state-of-the-art for reproducing important physical processes and for providing geographic detail. The geographic (horizontal) resolution of the GCMs that have been used for long-term climate studies ranges from about 8° × 10° to 2.5° × 3.75° with grid areas of hundreds of thousands of square kilometers. Many natural and human resources, however, are distributed on a much finer scale, with variations ranging from meters to kilometers. Clearly, analyses of the effects of CO_2 climate interactions on resources are meaningless on a global-average basis. In addition, climatologists are not able to predict future climate with a geographic resolution of meters to kilometers. Even if such climate data were available, it is uncertain that such detailed resource data and the methodology and computer facilities to perform the necessary analyses would be available.

The challenge, then, is to define appropriate regions and regional scales as the basis for analyses.

NEED FOR INTEGRATED, MULTI-RESOURCE ANALYSES

There have been a number of case studies of the effects of CO_2-induced climate changes on individual resources. For example, Rosenzweig (1985) examined the potential distribution of wheat production in North America as determined by the climate resulting from a doubling of atmospheric CO_2, using the climate predicted by the Goddard Institute for Space Studies (GISS) GCM. Blasing and Solomon (1984) predicted a shift in the North American corn belt based on a doubling of CO_2, using the Geophysical Fluid Dynamics Laboratory (GFDL) GCM. Cohen (1986) quantified the effects of a doubling of CO_2 predicted by both the GISS and GFDL GCMs on the net basin supply of the Laurentian Great Lakes. Solomon (1986) examined the climatic effects of a doubling and quadrupling of CO_2, as modified from the GFDL GCM, on North American forests.

However, two important conceptual shortcomings are associated with such studies. First, the studies examined only the effects of the CO_2-induced climate shift. The increased CO_2 concentration itself may also influence the response of the resources. For example, CO_2 enrichment of the atmosphere is expected to affect plant transpiration, water use, and photosynthesis. Thus, it could affect growth rates, leaf area index, species composition, irrigation demand, and a host of related factors and processes—ultimately even albedo, soil texture, and runoff characteristics. Therefore, the effects of the climate change as well as the CO_2 itself must be considered.

Second, natural and human resources do not exist, function, or change in isolation. They are connected by exchanges of matter and energy, goods and services, and competition for labor and land. Effects on agriculture may be determined in part by the availability of water for irrigation, and the availability of water supplies may be influenced by the interception and retention of precipitation attributable to agriculture. Agriculture and forestry may compete for the same land. Forest ecosystem types may determine the habitats available for wildlife species. If future climates affect production and consumption of natural gas for residential and commercial heating and cooling, the availability and cost of agricultural fertilizers could be affected. Thus, a resource such as agriculture cannot be treated in isolation.

REGION TYPE AND APPLICABILITY TO THE CO_2/CLIMATE PROBLEM

As shown previously, analyses that are regional, integrated, and multi-resource are needed to address the response of resources to changes in atmospheric CO_2 and climate. What is not known is which types of regions are optimal from the standpoint of resource analysis. The climate/resource studies referred to earlier are based on differing types of regions, and the type of region affects the use of climate and resource data as well as the assessment methodology. When conducting climate/resource studies, it is useful to identify three types of regions: boundary-defined regions, homogeneity-defined regions, and dynamics-defined regions (Waterhouse 1987).

Boundary-defined regions are delineated on the basis of convenient boundaries that are distinct and easy to determine. For example, the grid of a GCM may determine the regions, as in the case of the Rosenzweig study of North American wheat. With such an approach one may observe large-scale patterns and pattern shifts, with the advantage that the output from the GCM is directly usable. Unfortunately, resources may not be homogeneous within the region, as will be discussed in more detail later in this paper. For example, in the case of Rosenzweig's study, several varieties of wheat which differed in thermal and precipitation requirements were found in some grid cells, but it was necessary to characterize each grid cell based on the variety grown in the greatest acreage in the cell. Thus, there is some reduction of accuracy and detail in the resulting analysis.

Homogeneity-defined regions are delineated on the basis of maximum homogeneity of one or more variables. This permits uniform handling of data within the analysis, e.g., climate/crop regression models, and also lends itself to the development of uniform policy and management approaches. However, the boundaries of homogeneity-defined regions may be difficult to determine, particularly if there is continuous variation. Fine-scale variation may limit the amount of homogeneity that is ultimately attainable. In addition, when several resources are being considered simultaneously it is unlikely that maximum homogeneity can be preserved for all resources.

In their analysis of the effect of climate change on the North American corn belt, Blasing and Solomon used a homogeneity-defined region (the corn belt) as the basis for their analysis. However, it is difficult to relate the gridded output of the GCMs directly to the region of interest. Assigning specific grid points to the region and determining valid methods of interpolation between grid points is difficult. In the Blasing and Solomon study, the changes in temperature and precipitation inferred from the GCM output were assumed to be uniform throughout the region. However, this assumption does not at all make use of the spatial resolution available from the GCMs. For a resource whose location or distribution is a function of climate, the location and dimensions of the region will also change, complicating long-term studies.

Dynamics-defined regions are delineated in order to maximize intra-region exchanges and minimize inter-region exchanges. Such regions are integrated units and are appropriate for interfacing with dynamic spatial systems models. For some dynamics-defined regions such as large drainage basins, regional boundaries are easy to determine. However, for others such as economic regions, defining boundaries may be more difficult. Furthermore, variables may not be homogeneous within these regions, and shifts in interaction patterns—whether a result of CO_2/climate interactions or other factors—would be expected to alter some regional boundaries. In the case of drainage basins, regional boundaries are determined by topography and thus do not change with shifts in climate on the time scales being considered.

One example of the use of dynamics-defined regions in climate-change investigations is the study by Cohen on the effects of climate on net basin supply in the Great Lakes. In that study, the coarse resolution of the GCM output resulted in uncertainty in locating future climate patterns.

RESOURCE HETEROGENEITY AS A FUNCTION OF REGION SIZE

As discussed previously, resources are not necessarily homogeneously distributed within boundary-defined regions. In the Rosenzweig study of climate effects on wheat, heterogeneity of wheat variety within the boundary-defined regions (GCM grid cells) led to simplifying assumptions concerning the resource. An obvious question is: How small must a region be to minimize the problem of resource heterogeneity?

Cushman et al. (1986) examined the heterogeneity of five resource variables—wheat yield, population density, percent forest cover, water resource regions, and percent of land irrigated—as a function of GCM grid cell size. They found that there was little improvement in resource homogeneity from grid cells approximately 8° × 10° to grid cells approximately 3° square. However, a further increase in resolution to 0.5° square resulted in a marked increase in resource homogeneity. This result was found in all five resources even though the five were markedly different in type and distribution, and despite the fact that the water resource regions were based on exact boundaries while the other four types were quantified with county-averaged data.

For climate modeling, possible solutions include:

- increasing the resolution of the entire model grid, which would greatly increase computing requirements
- increasing the resolution of certain grid cells in areas of particular interest; and
- using empirical orthogonal functions to associate likely detailed distributions of climate with larger-scale climate patterns based on analysis of past data (e.g., Gates 1985), although such distributions may also change as global climate patterns change.

PROSPECTS FOR THE FUTURE

Integrated, multi-resource analyses on a regional level are needed to assess the consequences of increasing atmospheric concentrations of CO_2 and the resulting climate changes for renewable and non-renewable resources. The effects of both CO_2-induced climate change and the CO_2 itself must be considered simultaneously; similarly, the various resources and their interactions and feedbacks must also be considered in tandem.

The US Department of Energy, through its Carbon Dioxide Research Division, is currently sponsoring research on this problem. One aspect of this research is the development of methods to refine predictions of climate change on a regional scale. In addition, emphasis is now being placed on the development and refinement of analytical methods for multi-resource, regional effects analyses.

Some of the future questions to be addressed are: What types of regions or combinations of regions are optimal for analysis? Which resources are of greatest importance? Which cause-and-effect models are most appropriate—regression or simulation? What resource interactions and feedbacks need to be considered? How should resource data be managed and aggregated to regional levels?

ACKNOWLEDGMENTS

We thank R.E. Millemann and L.D. Voorhees for reviewing this manuscript. Research was sponsored by the Carbon Dioxide Research Division, Office of Basic Energy Sciences, US Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. [Publication number 2881, Environmental Sciences Division, Oak Ridge National Laboratory].

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The Use of Ambient Air Quality Monitoring in Assessing Regional Exposures to Toxic Air Pollutants

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The control of toxic pollutants is one of the most challenging environmental problems facing the regulatory community today. The number of substances of potential concern is extremely large, as is the number of sources—industrial and non-industrial—that discharge them. Ambient concentrations tend to be small, making detection and accurate identification technically difficult. Even if ambient concentrations are known, their significance is often difficult to determine. Ambient concentrations cannot be directly correlated with effective dose, and the toxicology aspects of the low dosages commonly encountered in the environment are subject to much debate.

With these considerations in mind, this paper discusses the role of ambient monitoring in estimating ambient concentrations of toxic pollutants in air. The US Environmental Protection Agency (EPA) has traditionally relied on ambient concentrations as a reference for regulation, but it is important to stress that estimating ambient levels is only a starting point in estimating exposure and effective dose for toxics. Exposure assessment requires determination of the magnitude, frequency, duration, and route of exposure to a certain pollutant (EPA 1986a). Ambient pollutant levels provide only a crude basis for assessment of these factors, as they do not take into account pollutant levels in occupational and indoor environments.

Other types of monitoring that can be used to support an exposure assessment include source monitoring and personal monitoring. Source monitoring is the direct measurement of emissions at a release point. It can provide an excellent means of obtaining representative emissions data as input to a dispersion model, but it is generally only feasible for sources with a limited number of well-defined release points. Personal monitoring involves placing monitoring devices on subjects as they conduct their daily routine. It provides data that are more representative than ambient outdoor concentrations since exposures inside residences, during transport, inside commercial facilities, and in workplaces are also considered.

EPA currently regulates only a small number of the pollutants present in the ambient air: particulate matter (measured as a total quantity, not differentiated by substance), sulphur dioxide, nitrogen oxides, carbon monoxide, ozone, and lead. These substances are controlled in terms of quantitative ambient standards known as the National Ambient Air Quality Standards (NAAQS). A handful of other pollutants are regulated in part through the National Emissions Standards for Hazardous Air Pollutants (NESHAPS). However, these standards are set, as their name implies, as limits on emissions, not as limits on ambient concentrations. By contrast, air in an industrialized metropolitan area is likely to contain many thousands of organic and inorganic compounds, including some which are directly released and others which are photochemically produced in the atmosphere.

Successful monitoring programs for air toxics should not be directly patterned after the type of monitoring programs developed for the "conventional" (i.e., NAAQS) pollutants which focus on accurate quantifications of a limited set of known substances in relation to clearly defined standards. By contrast, the number of toxic air pollutants of potential interest is so much larger and so variable from location to location that a major challenge of air toxics monitoring is simply to identify which pollutants are present and to rank them in priority order. Quantification of ambient values, while of equal importance, becomes one of several goals rather than the only goal. The multiple goals of pollutant identification, ranking, and quantification imply the need for iterative screening procedures.

A MULTIFACETED APPROACH TO MONITORING

Because of the expense of monitoring for toxic compounds, a promising approach for identifying and ranking pollutants in metropolitan areas is to couple monitoring programs with parallel efforts in developing comprehensive emission inventories and in conducting dispersion modeling. Emission inventories, including both point and area sources, yield estimates by compound of toxic air emissions. Associated ambient concentrations of toxic compounds can then be estimated through the use of dispersion modeling, providing an initial estimate of ambient values that can be used as a basis for designing a screening-level monitoring program. Results of such a monitoring program can in turn yield insights into the accuracy of the emission inventory and provide the basis for succeeding iterations.

The success of this type of approach depends on the reliability of each of the components. All have admittedly wide error bounds which should be individually considered.

Emissions estimates

Many complex industrial facilities release a wide range of organic and inorganic pollutants from process vents, storage tanks, and other unintended release points which cannot be easily monitored. This range of pollutants and sources greatly complicates the compilation of emissions data and effectively precludes direct measurements in many cases. A variety of estimating factors must therefore be used. These factors can include mass balance calculations which, although rough, appear to be reasonable in the aggregate. Where possible, detailed estimates can be made through process engineering studies. In addition, while estimates of releases from area sources cannot feasibly be developed through source monitoring, they can be reasonably approximated through indirect approaches such as evaluating total motor vehicle travel, regional gasoline sales, population density, and/or fossil fuel consumption for heating requirements.

Dispersion modeling

Although dispersion modeling results for short-term averaging periods have typically had wide margins of error, existing models have been found to provide reasonable estimates on a seasonal or annual basis. For evaluations of seasonal or annual averages, accuracy has generally been found to be within a factor of two (White 1984), which is adequate for the type of screening procedures suggested here. For short-term averaging periods such as 24 hours or less, the greater uncertainty in model output needs to be considered when interpreting results. Major sources of this uncertainty include the degree of accuracy of the models themselves and of the input data, which includes available meteorological and emissions data for the area under study.

Ambient monitoring

A variety of laboratory analytical techniques are available to support ambient monitoring programs. While levels of accuracy are improving, techniques are still expensive and their adequacy still widely debated. There are also substantial uncertainties about the representativeness of individual monitoring sites in any network. Although error bounds on any estimated ambient concentration are potentially great, monitored values at any given point can serve as a reference for gauging predicted values that have been generated by dispersion modeling using emission inventories as input data.

IEMP STUDIES

EPA's Integrated Environmental Management Program (IEMP) has used this general approach at a number of sites across the United States. The program has conducted, or is currently conducting, studies of toxic air pollutants in five metropolitan areas: Philadelphia, Pennsylvania; Baltimore, Maryland; Santa Clara County, California; the Kanawha River Valley, West Virginia; and Denver, Colorado. These studies provide practical examples of the use of integrated ambient monitoring and dispersion modeling as a means of estimating exposure to toxic air pollutants. Each of these metropolitan areas is different in terms of its mix of sources, terrain, and meteorology. The ambient monitoring programs designed for the sites were therefore different and made use of dispersion modeling in different ways. Two of these programs are discussed below as examples of iterative monitoring and modeling programs.

Philadelphia

Philadelphia is a major metropolitan area with a substantial heavy industry sector. The ambient air monitoring program developed for this study was the first urban-scale air toxics monitoring program for organic pollutants conducted by EPA. It involved a ten-station monitoring network set up to measure a limited set of volatile organic compounds. Dispersion modeling was performed prior to the selection of monitoring sites so that neighborhoods with relatively high concentrations could be identified. The program collected a total of thirty 24-hour samples at each site between December 1983 and March 1984 (EPA 1984).

The pollutants were selected on the basis of existing toxic chemical and air emission inventories compiled by the city of Philadelphia. These inventories were augmented by additional work conducted by the IEMP program, yielding a combined emission inventory that included all known point and area sources of toxic air pollutants. Dispersion models were then used to estimate ambient concentrations at each of the monitoring sites for the specific time periods when each sample was taken. Modeling was performed using meteorological data collected at a site central to the air quality monitoring network. The EPA model SHORTZ was used for the comparisons (Sullivan 1985).

The results were then compared. Agreement between the monitoring and modeling efforts was relatively good for about one-half of the compounds that were measured but was relatively poor for the others. The final report of the Philadelphia IEMP includes details of this statistical analysis. In general, agreement was better for those compounds emitted by a small number of well-defined industrial facilities. Figure 1 shows day-to-day comparisons of monitored and modeled values for one such compound: 1,2-dichloroethane. Poorer results were found for compounds emitted by both area sources and point sources or by a large number of distributed point sources.

The study provided a number of interesting insights. For example, when discrepancies between predicted and observed results were analyzed in relation to wind direction, it was possible to identify individual sources for which emission inventory estimates were low. In one case, emissions of trichloroethylene from a major garment manufacturer were found to be underestimated by approximately a factor of five because process emissions from

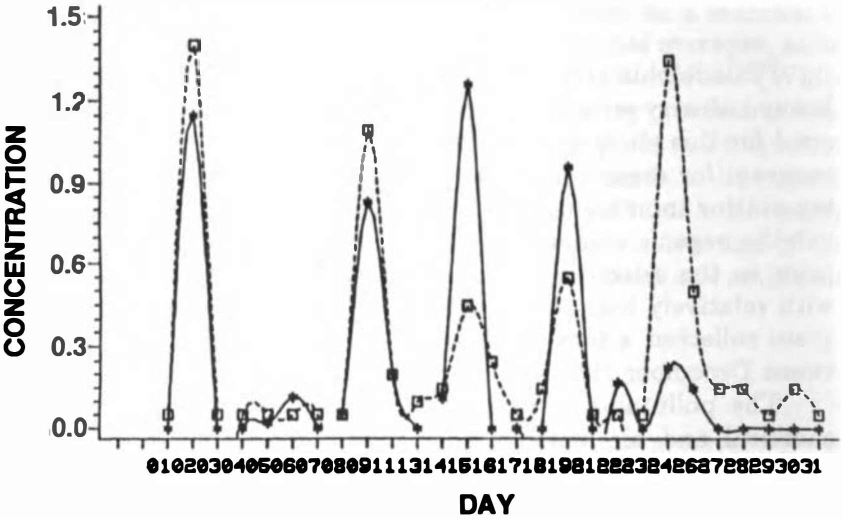

FIGURE 1 **Examples of a comparison of modeled (*) and measured (□) data: 1,2-dichloroethane at site 7 (ug/m^3).**

the recovery still were not addressed. In another case, volatilization losses associated with the transport of wastewater from a major organic chemical plant were identified after the modeled concentrations were found to be low for 1,2-dichloropropane and 1,2-dichloroethane. The parallel use of models and measured data can thus reduce the uncertainty in characterizing ambient concentrations.

The Kanawha Valley

The Kanawha Valley IEMP study is a good example of measured air quality data used to assess the reasonableness of model performance in complicated terrain. Kanawha Valley, West Virginia, is one of the largest manufacturing regions for organic chemicals in the United States. A winding valley roughly one to three kilometers wide bounded by valley walls approximately 300 meters high, Kanawha Valley experiences limited dispersion and high frequency flow past nearby residential areas. This region has the potential for high impacts from air toxics on populations in the vicinity of the major chemical plants.

In this study, detailed meteorological monitoring was performed in four valley sections having clusters of industrial sources.

A modeling analysis was then performed based on the detailed meteorological data which emphasized close-in, micro-scale concentrations (EPA 1985). Detailed emissions data were available for the major and minor industrial sources in the valley. The emissions were grouped into logical modeling units such as vent emissions from a common building and common storage areas. All stacks were modeled individually. The emissions inventory was complemented with area source emissions from mobile sources, dry cleaning facilities, and other urban sources. Emissions data were used in conjunction with meteorological data to model each of the four valley sections independently. A total of 14 specific organic compounds have been evaluated to date. Predictions were made of annual average concentrations throughout the valley floor portion of each of the sections studied.

There was considerable uncertainty regarding the effectiveness of dispersion models for this area. To help reduce this uncertainty, a monitoring program was designed to complement the modeling analysis. In two of the valley sections, ambient monitoring was performed up and down the valley from one to 2.5 kilometers from the fencelines of industrial areas. Over a two-month period, a total of fifteen 24-hour average samples were collected at each of the four monitoring sites to help assess the adequacy of the emissions data and to evaluate the reasonableness of modeled values in this complicated terrain.

This integrated modeling and monitoring approach is likely to be particularly useful in areas such as Kanawha Valley. In a valley, a small number of monitors can produce excellent reference points to assess the reasonableness of emissions data and model performance. This is because the flow is highly channeled on a very regular basis past appropriately located monitoring sites on the valley floor, i.e., wind flow often is restricted to the orientation of the valley.

Preliminary results generally show reasonable comparison between modeled and measured data, with some exceptions. In these cases follow-up work could be performed to reassess the emissions data and possibly improve model performance. For example, based on preliminary results, one section of the valley was found to have model estimates for some compounds that substantially underestimated measured concentrations. As in the Philadelphia study, this finding can be used to help provide focus to the emissions verification. Preliminary results also suggest that estimates down the valley tend to be understated relative to those up the valley. This provides input to reassess the adequacy of the modeling approach to account for the differences in dispersion conditions between transport of pollutants up and down the valley. The results of the Kanawha Valley study are expected to be available in early 1987.

CONCLUSIONS

In summary, estimating exposures to air pollutants in a large metropolitan area or in the immediate vicinity of isolated major industrial sources requires consideration of site-specific factors. No single approach applies to all situations. The consideration of modeling as a complementary tool to help design and evaluate measured data, however, can be common to all air quality studies. Measured data provide important reference points, while modeling can be used to estimate concentrations on a large scale and can better describe the variability of concentrations in space and time. When performed in a complementary and integrated manner, the two approaches of monitoring and modeling can be used to more accurately estimate ambient concentrations used in an exposure assessment.

There is considerable uncertainty in predicting or measuring concentrations of pollutants in the ambient air, especially for toxic air pollutants. Emissions may be uncertain for some pollutants which can adversely affect modeling while ambient monitoring techniques may be relatively poor or non-existent for other pollutants. The use of two approaches—dispersion modeling and ambient monitoring—to estimate concentrations can help fill the gaps of information in either approach, thereby reducing uncertainty. Identifying compounds for which modeling and monitoring results are in relatively close agreement, as well as those where results are substantially different, can be important at the often costly stage of control measure implementation.

Confidence is needed in the supporting technical data bases for a metropolitan area to develop policy alternatives that will lead to practical changes in the control of toxic air pollutants. The IEMP field studies have developed a technical approach that provides a reasonable basis on which to assess risk, as well as risk reduction benefits of alternative control measures within current limitations of state-of-the-art air quality analysis. Monitoring is an important element of the overall approach. The next step is to use this technical information to develop control options that lead to regulatory action at the Federal or local level which can effectively reduce risk at an acceptable cost.

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Monitoring Atmospheric Pollution: Norms and Standards—Policy and Practice

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The prevention of atmospheric pollution in the USSR is an essential prerequisite to providing Soviet citizens with favorable living, working, and leisure conditions. It is also necessary to preserve our forests, lake ecosystems, agricultural and other vegetation, animal life, and various structures including historical and cultural landmarks. This requirement is a result of the "Air Protection Law" passed in 1980, which regulates the rights and duties of central and local authorities, companies, organizations, and citizens in this area.

In organizational terms, the USSR's state air protection system consists of three basic components:

- Air pollution monitoring;
- Measures for regulating air quality;
- Implementation of pollution controls at the air pollution source.

AIR POLLUTION MONITORING

Air pollution monitoring in the USSR is conducted at three basic levels: impact, regional, and global.

Impact-level monitoring is a rapid information subsystem of continuous observations of air pollution from primary and discrete pollutants contained in gases emitted by factories and mobile sources. Monitoring is conducted with a network of stationary sites situated in major populated areas and on boundaries of protected zones adjacent to industrial centers.

The observations made by this network of stationary sites are supplemented by ongoing, on-site and plume observations using specially designed mobile laboratories. Impact monitoring is conducted in 460 cities and industrial centers, and approximately six million measurements per year are made. Data from impact monitoring are used in an operational system to direct inspections of air pollution abatement measures by examining specific facilities which are sources of air pollution.

Impact monitoring data analysis and annual retrospective overviews permit us to ascertain air quality trends in urban areas and industrial centers. This is essential for:

- Assessing the effectiveness of air protection measures for each city and republic and for the nation as a whole;
- Priority setting for optimizing planning of air protection measures and capital investments earmarked for this purpose.

Findings from impact data monitoring are also used to determine the background levels of air pollution. This is a key to:

- Adopting appropriate decisions for siting new production facilities and for expanding capacity of existing facilities;
- Compiling environmental impact statements for proposed construction and upgrading of facilities which will affect the atmosphere;
- Setting limits on contaminant discharges into the atmosphere for each significant pollutant release point.

Regional-level monitoring is conducted as part of EMEP, the international program of transboundary air pollution observations and assessment in Europe. These observations are conducted at ten specialized stations located on the USSR's western border. They annually include over 36,500 measurements.

The aforementioned observations of trace elements in the atmosphere and in deposition are supplemented by information from 26 vectors of transboundary air pollution at varying altitudes (up to five kilometers). Special aerial instruments are used to yield this information. The observations are complemented by data from monitoring the chemical constituents of precipitation and other information generated by a snowpack contamination monitoring network. This program yields data on deposition of atmospheric trace elements entrapped in snow.

Regional-level monitoring data under EMEP are incorporated into the computations made by the East European Synthesizing Meteorological Center (MSTs-V). Located in Moscow, this center provides the USSR and other East European countries with computations of transboundary sulphur compound fluxes and deposition. MSTs-V is currently conducting preparatory work towards compiling statistics on transboundary fluxes of nitrogen oxides and other pollutants.

Statistics compiled for several years by MSTs-V and corroborated by MSTs-Z located in Oslo have shown that from five to ten million tons per year of sulphur compounds of transboundary origin are deposited in the European USSR. At the same time, from 0.5 to 1.0 million tons from the USSR are deposited to other nations of Europe, that is, five to ten times less.

Global-Level monitoring has been conducted in the USSR since the early 1970s at four background BAPMoN stations. Two of these stations are situated within the European and two within the Asian USSR. Furthermore, global air pollution monitoring is also conducted at seven background stations operating under the comprehensive background monitoring program at USSR biosphere reserves: Berezinskiy, Caucasus, Prioksko-Terrasniy, Repetekskiy, Sari-Cheleksiy, Barguzinskiy, and Boroviy. The work of these stations includes measurements of the most important pollutants which cause impacts on the biota: sulphur and nitrogen dioxides, sulfates, ozone, lead, cadmium, mercury, arsenic, benz(a)pyrene, and PCBs.

AIR QUALITY CONTROL MEASURES

Technical air quality control policies in the USSR are developed and implemented by the State Committee for Hydrometeorology, with the participation of other pertinent ministries and departments. This means that the State Committee for Hydrometeorology corroborates and executes all basic regulatory documents, such as standards, regulations, methods, instructions, and recommendations regarding air protection efforts.

Air quality control measures in the USSR operate in four primary areas:

- Coordinate siting of new production facilities and prepare impact statements regarding the construction of new and upgrading of existing facilities;

- Set limits for each plant on contaminants emitted into the atmosphere (Maximum Permissible Emissions–MPE);
- Annually plan and implement air protection measures in the form of government goals for businesses, organizations, production facilities, ministries, departments, and republic Councils of Ministers;
- Carry out comprehensive measures to reduce pollutant emissions from mobile sources.

Coordination of New Construction and Preparation of Impact Statements

The steadily growing expansion of production requires increasing material and labor expenditures for protecting the atmosphere from contamination. Such steps are most effective when the development and execution of air protection measures are initiated at the earliest stages of a plant's construction. As a result, Article 13 of the USSR's "Air Protection Law" calls for strict adherence to standards regarding safe levels of contaminants and their impact on the atmosphere when siting, designing, constructing, and putting into operation new and upgraded plants, buildings, and other facilities.

To achieve this, consideration must be given to the entrapment, utilization, and neutralization of contaminants from emissions or to the total exclusion of pollutant discharges. Additional air protection requirements also must be considered, bearing in mind that the total emissions from already existing plants and from those projected or planned for construction should not exceed the standards set for maximum permissible concentrations of pollutants in the atmosphere.

Impact statements for new projects are part and parcel of the analysis of projected construction. We can then evaluate the quality of our information. This includes assessment of data which are the basis planning, the effectiveness of engineering and planning decision-making, and the reliability of statistics used in forecasting air pollution.

A primary task related to impact statements for new construction is the comprehensive monitoring of compliance with the standards set for the project. Experts have focused much attention over the past 10 to 15 years on analyzing the technical upgrading of methods and equipment used directly in efforts to preserve air quality equipment employed in a plant's basic production. This reflects the fact that a project's economic and ecological indices are ultimately dependent upon fundamental decisions regarding the technology used in the production process.

The following aspects are considered in examining air protection measures:

- Validity of process of selecting site and area for construction. This selection must take into account background air pollution and physical, geographical, and meteorological factors, as well as the specifics of the project;
- The advanced character of chosen manufacturing processes, with a view to precluding or reducing pollutant formation and discharge and including a comparison of the selected technology with the best domestic and foreign technologies;
- Reliability and effectiveness of technical decisions taken with a view to protecting the atmosphere from pollution;
- Validity and reliability of data on pollutant discharges into the atmosphere;
- Accuracy of computations of changes in air pollution measurements as a result of the opening of a newly-constructed facility;
- Setting standards for maximum permissible concentrations of pollutants released into the atmosphere;
- Cost effectiveness of proposed air protection measures.

Norms and Standards

Maximum permissible pollutant concentrations (MPC) are used in assessing actual and predicted levels of air pollution in the Soviet Union. These standards should serve to protect the health of both the population and the environment. MPC standards for evaluating living conditions (i.e., sanitary and hygienic standards) are used by the USSR Ministry of Health. The USSR Ministry of Forestry and the USSR State Committee for Hydrometeorology jointly set similar standards which are of an ecological nature (e.g., MPC standards for woodlands vegetation, or MPC-W).

Maximum permissible concentrations of air pollutants in populated areas for one-time and for mean daily emission levels are currently in effect as national standards. Government regulations have been set for more than 300 contaminants, over 40 of which have an additive impact. In addition, approximately safe impact levels (ASIL) have been set for more than 300 air pollutants. In areas of the USSR set aside for health-care purposes, standards are in effect which are 20 percent more stringent than usual.

The Ministry of Health has also developed standards for maximum permissible ambient pollutant concentrations in the workplace. These currently total 976 and are taken into account in assessing accumulated and predicted air pollution levels not only inside buildings, but also in outdoor production areas of manufacturing plants. Other norms and standards are also employed which deal with automotive gas exhaust emissions, permissible noise levels, and the effectiveness of standard gas treatment and dust entrapment equipment.

Standard Setting for Discharges from Air Pollution Sources

In order to ensure compliance with sanitary, health, and ecological air quality protection standards for each pollutant release point, limits on contaminant discharges—called maximum permissible emission limits (MPE)—are set.

MPE standards are set for each pollutant and are determined to ensure that each discharge of emissions from discrete and other sources in a given area (mindful of potential growth) do not create a near-surface concentration in excess of MPC for the population, vegetation, and animal world.

In other words, the following correlation must be fulfilled:

$$\frac{C}{MPC} \leq 1$$

where C is the calculated concentration in the atmosphere's near-surface layer from the sum of its pollution sources. The MPE standard is determined using methods for calculating the maximum permissible emission level so that the pollutant concentration in even the most unfavorable meteorological conditions would not exceed the established health and hygenic MPC standards.

The calculation is made by the following formula:

$$MPE = \frac{(TiDK - Cb)H^2 \sqrt[3]{V_1 \Delta T}}{A \cdot F \cdot m \cdot n \cdot t}$$

where Cb = background concentration; H = release point height above the ground; V = flow rate of the air-gas mixture; T =

temperature differences between the air-gas mixture and the air; A = coefficient for the pollutant's meteorological potential; F = coefficient accounting for the pollutant deposition rate in the atmosphere; m, n = coefficients accounting for conditions of the air-gas mixture discharge at the mouth of the release point; and t = coefficient for the impact of local terrain on trace element dispersion.

MPE standards have been set for both existing and newly built plants, and are developed by profile planning organizations. In those instances where existing plants are not in compliance with the MPE, a variety of measures are employed to reduce emissions levels of pollutants to the computed MPE standard. Temporary, agreed-upon emission standards (TAE) are drawn up. These bring the plant in question into compliance with the MPE by implementing in one or more stages the technical measures developed as MPE was computed. If the established MPE standard cannot be met through technical measures, the activities of that particular facility are re-examined in order to reduce capacity, orient its main production to a more advanced technology, or convert the plant to a new type of production.

Standards have currently been set for plants whose emissions total approximately 75 percent of the nation's industrial emissions. It is planned to extend these standards to 95 percent of all industrial emissions by 1990. The established MPE standards and the measures which have been developed to achieve them provide a sound basis for planning governmental air protection efforts and for developing impact statements to test measures to maintain air quality.

Planning Air Protection Measures

Planning air protection measures is one of the most important steps in the regulation of air quality. As already noted, there are many principles underlying air quality measures. These include using information from impact- and regional-level air pollution monitoring and developing measures to reduce harmful emissions to the maximum permissible levels as prescribed by MPE and TAE.

Planning air protection measures is one component of the "Protection of Nature" section in annual and five-year state plans for economic and social growth of the USSR and the individual republics. The USSR governmental plan for each republic ministry and department, as well as for the republic Councils of Ministers, sets out concrete goals for the removal of pollutants from gas emissions (in tons per year); for reducing the amounts of harmful emissions released into the atmosphere; for introducing dust and gas treatment equipment with a capacity of millions of cubic meters per hour; and for allocating capital investments for air quality measures.

The total emissions figures broken down by industry branch cover all plants for each branch. They are first developed at each plant by accounting for existing and anticipated conditions. They are then aggregated at the ministry level. After the Supreme Soviet of the USSR incorporates these figures in the state plan, they become law and must be followed.

Regulating Mobile Source Emissions

Mobile source emissions currently account for about 40 percent of the total volume of emissions, and a noticeable growth trend for these emissions has been detected. This can be attributed to the fact that the number of automobiles continues to increase more rapidly than reductions of individual emissions occur.

Efforts to reduce harmful mobile source emissions in the USSR can be broken down into the following basic areas:

- Perfecting an engine to reduce fuel consumption and exhaust;
- Reducing gasoline toxicity by replacing tetraethyl lead with methyltretyethyl ether as a fuel additive, and replacing gasoline with diesel fuel or compressed or liquified natural gas;
- Implementation of exhaust neutralizers;
- Expansion of public transportation (particularly subway, trolley, and tramway systems) instead of more pollution-intensive forms;
- Organization of traffic (the "green wave," underground passageways, exits, etc.);
- Improving automobile servicing (auto emissions testing stations, toxicity testing, etc.);
- Re-examining auto emissions standards to make them more stringent;
- Enhancing ecological monitoring of mobile sources.

Immediate Measures for Regulating Air Quality

Urgent measures are initiated during episodes of unfavorable meteorological conditions (UMC). A special UMC warning system based on weather forecasts has been established in 120 Soviet cities with high incidences of UMC. These warnings are transmitted to city executive councils made up of peoples' deputies and to all plants that are major sources of toxic dust and gas emissions. Each plant has developed special measures to cut harmful emissions in the event of an UMC episode. They call for switching boilers to low sulphur fuel, utilizing backup gas and dust treatment capacity, reducing primary production output, and so on. These UMC warning measures are currently in place and serve to prevent dangerous air pollution levels. Monitoring compliance with these measures is conducted by state air protection inspectors and industry branch environmental services.

INSPECTION OF AIR POLLUTION RELEASE POINTS

Inspection of pollution release points is conducted in the USSR by the State Inspection Agency for Air Protection. It is assisted by the Ministry of Health and the Ministry of the Interior's Department of State Automotive Inspection. The State Inspection Agency for Air Protection monitors compliance by plants, organizations, and citizens with the Air Protection Law. The State Agency visits plants to test gas/dust treatment equipment for efficiency and verifies the extent to which air protection plans are met. This includes air quality measures and other aspects regarding compliance with the law.

If an inspection team detects violations, it acts in accordance with its instructions or imposes penalties by:

- fining managers and specialists;
- submitting material to an administrative commission to serve as a basis for levying fines;
- transferring the case to the prosecutor if the violations constitute a criminal offense;
- shutting down specific plant sections, production lines, or entire plants.

Use of Environmental Data in Management Decisions

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Although the US Environmental Protection Agency (EPA) invests heavily in environmental monitoring, information on environmental quality and trends in pollutant levels are not adequately used for management decisions in many programs. Monitoring information has historically been used to set national standards, to determine limits in individual permits, and to support enforcement actions. However, environmental monitoring is not routinely used to compare the severity of problems across media (e.g., air as compared to surface water contamination) or to set priorities. In an era of limited resources and increasingly subtle and difficult environmental concerns, the value of environmental data in environmental policy and management decisions is becoming increasingly important. This paper considers the need for additional information for environmental management, and then briefly covers several activities now underway in EPA to improve the type, quality, and availability of environmental data.

TECHNOLOGY-BASED CONTROLS VS. MANAGING FOR ENVIRONMENTAL RESULTS

The laws which EPA implements depend heavily on generic, technology-based controls on specific classes of sources. The assumption has been that environmental improvement would follow the control of significant sources such as reducing pollutant loadings. For example, the Clean Water Act required controls on municipal and industrial discharges according to national standards regardless of the location of these facilities.

Since the early 1970s, the variety of environmental problems has grown, and in many cases these problems are not found uniformly across the United States. More importantly, in many areas regulations have not resulted in an improvement in environmental quality. With regard to water pollution, for example, controls may have reduced loadings from point sources for specific chemicals for which standards exist and permit limits are set, but other sources—such as runoff from urban or agricultural areas or discharges of unregulated chemicals—may continue to degrade water resources.

Ultimately, environmental agencies must assess whether technological controls are protecting or improving environmental quality using measures of human morbidity and mortality and plant and animal survival. This requires identifying human and ecological effects of concern and then establishing methods to measure and interpret change.

THE NECESSARY MIX OF ENVIRONMENTAL DATA

As EPA's programs have matured, the need for a broader mix of environmental data has grown. Figure 1 describes a continuum of data types available to managers for assessing the effectiveness of their programs. The left side includes those data that are measures of regulatory activity. The extreme right includes data that directly measure the effect of those activities on human populations and on fish and wildlife resources. The data in the center include discharge quantities and data on ambient pollutant levels in the environment.

All data types are needed for sound environmental management. At present, however, the proportions of available data are not in balance. Instead, the amount of resources spent on each data type drops off precipitously from left to right. US environmental managers do not currently have every data type available for all areas of environmental concern. The goal is to identify the necessary data to assess changes in quality and assure that they are collected and used.

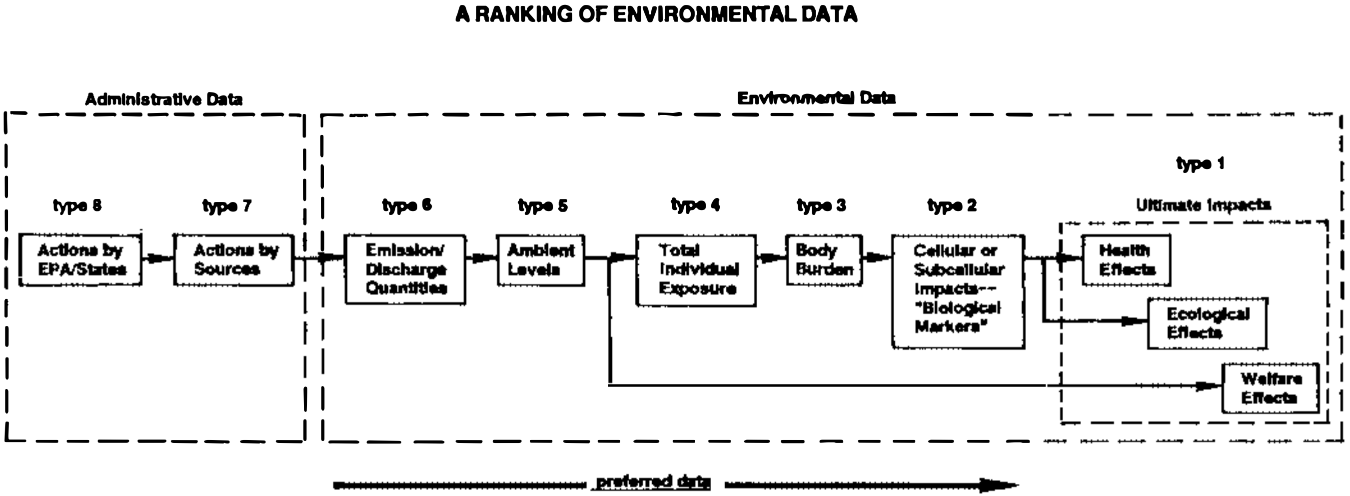

FIGURE 1 A ranking of environmental data.

Data to the right are closer to the "adverse impacts of pollution"—the ultimate, observable, adverse impacts that result from environmental risks. All else being equal, data further to the right are better measures of the current extent and severity of environmental risks and of effectiveness in efforts to mitigate these risks.

Data are ranked in the form in which they were *originally measured*, not in the form in which they are *presented* after further analysis.

LONG-RANGE PLANNING AND ENVIRONMENTAL INDICATORS

In 1985, EPA began to apply the concept of managing for environmental results to the development of long-range plans for major environmental issues. Planning was begun in five areas: wetlands, agricultural chemicals in groundwater, air toxics, intermedia transfer of hazardous wastes, and near coastal waters. These plans are designed to predict the future effects of management decisions. Essentially, the planning process applied to environmental issues answers the following questions:

- What is the present condition of the ecosystem? What are the current environmental problems and the sources of these problems? How widespread and significant are they?
- What will be the condition of the ecosystem in 10–15 years, given projected uses and current approaches to managing these problems?
- What should be the condition of the environment, based on present or projected future expectations regarding the degree of environmental quality?
- What can be done and what are the tools needed to achieve the desired results?

The answers to these questions should lead to development of a set of possible actions by varying levels of government (e.g., EPA, individual states, or federal agencies and the states) to achieve some future level of environmental quality. One of the key steps is determining what environmental data are needed to support effective action within the strategic plan.

MEASURING SUCCESS: ENVIRONMENTAL INDICATORS

At the heart of this planning initiative is the concept of environmental indicators. Environmental indicators answer the question: If this problem is addressed successfully, what change in environmental quality, human health, or other "ultimate impacts" would be expected?

An environmental indicator is an environmental variable, concept, or aggregation of data that provides a surrogate representation of some aspect of environmental quality or condition. For example, one indicator of the ecological state or condition of an estuary is the degree of enrichment of the water. A number of variables such as nutrient concentrations, productivity, biomass, and dissolved oxygen collectively provide a measure of the degree of enrichment.

The medical model is conceptually useful when considering indicators. A patient complains he does not feel well, and the doctor checks certain indicators such as temperature and appetite to determine how the patient's current condition varies from the ideal. Once the patient receives a diagnosis, action is taken in the form of medication or an operation. The physician and patient ensure that these steps have been followed but also continue to make use of the indicators of health to see how effective the remedies have been. The same is true for "curing" environmental problems.

Indicators are potentially powerful tools for highlighting significant environmental conditions, illustrating major trends, formulating environmental goals, and measuring progress toward these goals. They can be used in diagnosing environmental problems, developing environmental control programs, and determining the extent to which these programs have succeeded. Indicators can also be effective in defining alternatives, assessing trade-offs, and informing laymen, environmental managers, and policy makers about the current status of environmental quality and the extent of changes over time.

Returning to the medical model, the temperature of the human body is a sensitive indicator that either something is wrong or that the body is functioning normally. This single variable is a surrogate for a host of other variables. A patient does not have to understand the scientific principles underlying a change in temperature, nor does it matter whether the instrument used is an inexpensive mercury thermometer or a more expensive transistorized machine. What is important is that the indicator—temperature—reliably reflects a large number of changes that have an impact on human health.

Given current technology and understanding, it may be impractical to construct an environmental counterpart to human body temperature that provides such a clear relationship between the indicator and the underlying condition it measures. Some environmental problems have not been fully characterized and precise cause-effect relationships cannot yet be specified. Therefore, appropriate corrective actions cannot be identified with any high degree of certainty.

The issue of acid deposition illustrates this point. Initially, the hydrogen ion concentration in aquatic ecosystems was measured and the phenomenon was discussed in terms of negative effects on aquatic plants or on the development of fish eggs or early life stages. Now it appears that acidification of aquatic systems might result in the release of heavy metals bound in sediments or soil with a subsequent accumulation of these metals in fish or their occurrence in drinking water. Thus, what was initially a complete measure of effects now needs to be augmented to reflect a better understanding of the problem. Another measure which could be added to the set of variables describing the effects of acid deposition might be accumulation of heavy metals in larval fish.

The measures or indicators selected for each environmental problem should have certain desirable characteristics:

1. *Relevancy*: Statistical data sets which characterize the measure must provide information about the condition of an important resource or about the status or trend of an aspect of environmental quality that is of concern (e.g., reductions in toxic loadings to streams from municipal treatment plants).
2. *Sensitivity*: The measure must be capable of portraying ranges of environmental quality that reflect "normal" conditions, a "problem threshold," and a category that warns of serious environmental or ecosystem degradation. The indicator should be designed to respond within a timeframe appropriate to the environmental medium or process that is being measured.
3. *Selectivity*: The fewest number of environmental measures needed to describe and assess the condition should be used.
4. *Data Availability*: Data from sources realistically available in the public domain or easily collected should be used.
5. *Good Statistical and Scientific Quality*: There should be agreement among recognized experts that the data represent reasonably valid measures of some environmental condition.
6. *Scope*: (a) *Spatial*: The most desirable data are site-specific data sets for political units such as counties or geographic units such as watersheds or drainage basins that can be aggregated to show national trends. Less desirable, but often more available, are data based on statistically representative random samples from the nation as a whole that cannot be disaggregated to show local status or trends.

(b) *Temporal*: Time series data, which are collected regularly at the same place with the same methods, are most desirable to establish trends. However, even data collected at different locations, with different methods, and over a varying time interval can be of some value.

7. *Acceptability of Cost*: The costs of feasible corrective actions require careful analysis.

USE OF ENVIRONMENTAL DATA IN MANAGEMENT DECISIONS

Assessment of trends in environmental indicators and ultimate effects can provide significant insights for program management. For example, trends in levels of enrichment in estuaries can be used to determine the most appropriate targets for regulatory action with limited resources and over time, to assess the effectiveness of control strategies.

An example from the control of ozone in the lower atmosphere is illustrative. Under US law, health-based standards for levels of air pollutants were established for six major pollutants which serve as measures of air quality. The frequency and extent of violations of these standards can be used to indicate progress in controlling ozone pollution. Nationally, ozone levels over the past ten years have indicated a trend of reduced levels. However, a different perspective is provided by measuring ozone at specific locations. For example, while levels in Boston appear to be at about the national standard, levels in Los Angeles continue to be significantly above the standard.

Several management decisions can be drawn from such information. The ozone control strategy appears to be effective in some parts of the country while in other areas, such as Los Angeles, significant problems remain. The manager can either elect to revise the national strategy for ozone or determine the causes of the problem to provide the basis for a unique strategy to address conditions in a specific area.

These conclusions could not be drawn without appropriate, high quality, air monitoring data. While air quality standards are health-based, another level of data could be collected to assess the ultimate effects of ozone and the success of the control program, which could include incidence and severity of emphysema.

INNOVATIVE MONITORING METHODS

Clearly, increased use of environmental data for management could add substantially to the already high cost of collecting data to support other needs. Collection of detailed chemical data for all streams, lakes, and rivers, as well as collection to satisfy the requirements of some current environmental concerns such as air toxics and ground water, could easily double the monitoring budgets of EPA and the individual states.

Environmental scientists at EPA and other research organizations have been seeking ways to collect new types of data that could be used—like the conceptual model of temperature in the human body—to provide a general indication of environmental health. These data would provide early warning of concerns which could be addressed in more detail as necessary to correct the problem.

For example, much research has been conducted using fish populations as indicators of the health of water bodies. Careful monitoring of fish populations, species diversity, and fish pathology provides a clue to the chemical condition of the water. The status of fish populations could serve to reflect the overall health of the stream both for pollutants and loss of habitat.

While monitoring the tremendous array of toxic contaminants in the nation's streams would quickly expend monitoring budgets, fish populations could be used as an indicator of whether the mix of pollutants is at a sufficient level to show effects. EPA is working to establish expected standards of fish populations for the different "eco-regions" in the United States based on reference streams to indicate populations that would be expected without anthropogenic disturbances. Deviations from these standards could be used as an indicator of a problem, stimulating more detailed chemical analysis. Thus, monitoring of fish populations instead of monitoring chemical concentrations in water might provide substantial savings in terms of cost.

COMPARATIVE RISK BASED DECISIONS: THE FUTURE

EPA is now moving toward establishment of a more direct linkage between priority setting and the level of risk posed by different environmental problems. Any risk calculation must include both consideration of the variation in effects with changes in exposure to a given pollutant or disturbance and an understanding of the current exposure to the pollutant or effect. Therefore, monitoring data are critical to the success of risk-based decision-making.

EPA has initiated an effort to compare the risk of environmental concerns across media. For the past year, multi-disciplinary teams have been ranking major environmental problems in order of severity for four types of risk: cancer, non-cancer health risks, ecological risks, and welfare risks. While this activity is scheduled for completion in early 1987, some valuable lessons have already been learned. In some areas, particularly regarding ecology and welfare, the ability to understand and calculate risks is severely limited. Furthermore, in many areas key data are not available to assess risk. For example, in attempting to calculate ecological risk from loss of wetlands, fundamental data on the rate of loss are lacking, as is specific information on changes in animal populations and water quality where significant losses have occurred.

In conclusion, environmental decision-makers are facing increased pressure to set priorities and direct resources to those activities which will bring the greatest positive change in environmental quality for a given "investment." EPA is attempting to identify those decisions which can be made from a risk-based perspective and determine what data will be required. It is not an easy transition. Historical approaches which have concentrated on regulating the largest and most easily controlled sources need to be augmented to reflect better awareness of location and severity of continuing environmental effects. In many cases, smaller sources and sources not easily controlled will require much greater attention in the future.

Preserving and Regulating the Ecological Function of Topsoil

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As scientists focus increasing attention on the study of the biosphere, the pivotal role of soil becomes increasingly obvious. It serves not only as the foundation of agriculture but also as an irreplaceable component of all terrestrial ecosystems and the biosphere as a whole. Highly complex processes of exchange involving matter and energy between the earth's crust, the atmosphere, and the hydrosphere take place in soil. Soil serves as an extremely fine biological and mineral membrane on the earth's surface and all organisms, including man, are involved in these exchange processes.

Soil is regarded not only as a unique natural body, but also as a special, multi-functional, biological and mineral system which plays a leading role in maintaining biosphere stability. Soil's many ecological functions can be broken down into two categories: biogeocenotic (ecosystemic) and global-biospheric.

Soil serves as a habitat for a wide diversity of organisms, one of the most important functions it performs in biological and geological ecosystems. First of all, its three-phase system (solid, liquid, and gaseous) makes soil a unique habitat. Second, it is an organic, mineral system and is therefore suitable for both autotrophic and heterotrophic organisms. Third, soil is a system with many different dispersion channels; it is structurally heterogeneous with a wide variety of ecological pockets. These factors create ecological conditions which provide a favorable habitat conducive to the vital activity of abundant and diverse organisms.

It is a well-documented fact that soil, as a habitat, has a tremendous density and a very high level of geochemical energy of living matter. The biological mass of terrestrial biological and geological systems exceeds the biomass of the seas and oceans by 750-fold, despite the fact that the total land area is three times less than the water areas. In addition, species diversity of land organisms is incomparably greater than the diversity of organisms inhabitating the aquatic environment. Diverse organisms find soil a medium with highly favorable conditions for living space, water, air, nutrients, and protection from precipitous fluctuations in hydrothermal conditions.

One of the most important ecological functions of soil is its geological productivity and fertility, on which agriculture and forestry depend. Soil fertility provides man with 90 percent of his nutrients and a broad range of raw materials used in industry (woodworking, textiles, chemicals, etc.). Soil also serves as a major energy bank since soil humus contains as much accumulated solar energy as is present in all surface vegetation. Soil performs a tremendous two-way process of organic matter accumulation and destruction, highlighting the cyclical nature of terrestrial life processes.

The global-biospheric functions of soil are seen in its association with the lithosphere, hydrosphere, and atmosphere. Soil is the earth's living, functioning "skin" and serves as a kind of "roof" for the lithosphere, protecting it from destruction by the exogenous processes of denudation and erosion. On the other hand, soil constitutes the uppermost horizon of the hypergenesis zone where highly active biochemical processes transform the granular size and mineral composition of rock, gradually accumulating fine soil and the most finely dispersed portion of the undersoil.

The functional impact of soil on the hydrosphere is reflected in its transformation of the chemical composition of precipitation by percolation through soil to form groundwater, river water, and ultimately sea water. As V.I. Vernadskiy noted, the salinity of sea water is primarily a function of the chemical action of soil. Through its so-called "respiration," topsoil exerts no less an influence on the dynamics of chemical composition, humidity, and temperature of the near-surface layers of the atmosphere.

The salient role of soil in the processes at play in terrestrial ecosystems and the biosphere at large is clearly evident from even a brief and incomplete perusal of its ecological functions. Therefore, a specific soil protection strategy which would optimize these ecological functions needs to be developed if we are to maintain biosphere stability. Such a strategy must be based on an ecological evaluation of the structural and functional role of soil cover. This kind of strategy would have to take into account those properties of both soil and topsoil which best define specific ways of protecting and preserving soil from destruction, pollution, and incorrect usage. The following specific soil properties must first and foremost be considered:

- In contrast to the atmosphere and hydrosphere, soil is not capable of dispersing those components which are contained in it or introduced to it. As a result, any contamination of soil (from heavy metals, radioactive elements, hydrocarbons, pesticides, and other toxic elements) will in most instances have long-term effects which are difficult to counter.
- Topsoil is extremely delicate and biogenetic and therefore is the most easily damaged of the earth's geospheric membranes.
- Topsoil is geographically highly variegated and diverse; it includes hundreds and even thousands of soil types which differ greatly in their properties, conditions, and ecological features. Measures to protect the soil and regulate soil processes must therefore be rigidly differentiated to account for zonal and regional differences.
- The age of mature, fully formed soils is measured in thousands and tens of thousands of years. The topsoil of large areas is therefore a virtually unrenewable fund of one of our most important natural resources.

Maintenance of biosphere stability calls for organizing a global soil monitoring program and developing a regional and zonal system with an ecological approach to optimize and regulate soil use. Soil monitoring must be a subsystem of an integrated ecological monitoring program which should be carried out at three levels: global, regional, and impact. The goals of a soil monitoring program, its control indices, monitoring methods, and measurement periodicity have at this stage been more or less developed. They provide for monitoring changes in soil reaction (acidification or alkalization), salinization (particularly in irrigation zones), humus content, soil contamination from various toxic substances, soil biota activity (nitrification, etc.), erosion, marsh formation, and diversion of land for industrial, residential, and transportation uses. The soil monitoring network itself is still in the preliminary stages of development and therefore must be accelerated and further refined.

Proposals to create an "Endangered Soils List" similar to the list of rare and vanishing plant and animal species merits our support. Soil possesses a highly developed "memory capability," an ability to record and preserve the long-term history of soil formation and the evolution of natural topography. Soil monitoring data should serve as baseline information for policy decision-making for soil protection and for offsetting negative trends resulting from man-induced topsoil evolution.

An extremely important aspect of maintaining and regulating the ecological functions of top soil is determining the ecologically permissible or optimal ratios of land area devoted to various branches of economic activity (agriculture, forestry, fisheries, water supply, national parks, recreational use, industrial and urban areas, and transportation), as well as ratios within each branch (e.g., the ratio in agriculture between arable land, meadows, pastures, and water use areas). In developing criteria for optimal soil use in different zones and regions of the world, it is important to account for the geographic diversity of potential soil resistance to such negative factors as:

- Water and wind erosion of soils;
- Soil destruction and contamination associated with man's technological activity (heavy metals, hydrocarbons, coal and cement dust, mining wastes, pesticides, and excessive and imbalanced doses of mineral fertilizers);
- Secondary salinization, cementation, and marshland formation where land is irrigated for agricultural use and subjected to fundamental transformation.

The development of zonal and regional models of the most efficient use of topsoil, which would account for soil's potential resistance to anthropogenic destruction and contamination, calls for an analysis and generalization of multi-scale soil maps, maps charting the economic uses of land resources, special maps of areas prone to erosion and secondary salinization, as well as soil-geographical and soil-geochemical maps which provide a regional breakdown of our land resources. By systematizing and generalizing these materials, we can then begin to compile maps charting topsoil preservation and the most ecologically sound use of topsoil in order to maintain biosphere stability.

Development of Scientific Information for Acid Rain Policy

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APPROACHES TO RESEARCH MANAGEMENT

There are two major objectives in support of national research programs. One is the support of those activities which show the most promise in furthering scientific understanding. The other is the support of research activities which address specific societal needs for information. Pursuit of both objectives is, of course, important; however, the two objectives lead to different priorities and therefore require different processes for priority setting and program management.

Research pursued primarily to further science can be managed to a very great extent within the scientific community. Priorities can be established and individual projects selected through the collective judgement of peer groups within and among the various scientific disciplines. The role of the non-scientist in this process is primarily that of contributing to the broader societal decision of determining what portion of a nation's resources should be dedicated to the pursuit of general scientific inquiry.

This is not the case, however, for research targeted to a specific societal need for information. Under these circumstances, there emerges an end-user or client for the information, and the establishment of research priorities becomes the shared responsibility of the client and the scientist. Developing the scientific and technical basis for sound environmental protection decisions is a prime example of a situation in which the relationship between researcher and end-user must be carefully established and maintained.

THE ACID RAIN EXAMPLE

The current US research effort on acid rain reflects a major attempt to manage scientific research for the purpose of providing direct support for environmental policy development. During the summer and fall of 1983 the US Environmental Protection Agency (EPA) conducted an extensive review of the state of scientific understanding of acid deposition and the policy alternatives available for its management. Based on this review, the US Government concluded that the high level of uncertainty in several key scientific areas precluded making a prudent choice between various policy alternatives. The Government therefore decided to defer its decision concerning appropriate action until sufficient additional information could be developed to significantly reduce this uncertainty. At the time of this decision, the Government already had initiated a sizeable acid deposition research program, with a budget of approximately $35 million in fiscal year 1984.

Because US policy was to defer a decision on the need for additional controls until the major scientific uncertainties had been addressed, EPA had the responsibility to clearly identify these uncertainties and to ensure that the ongoing research effort addressed these problems in the most expedient manner possible. Two issues soon became quite clear. First, it was not until after attempting to formulate a policy that the scientific areas most critical to policy development became apparent. Second, when the list of information needs was compared to research efforts then underway, it was clear that there were major gaps and mismatches.

For example, major emphasis had been placed on the development of a highly advanced source/receptor model to predict changes in deposition patterns associated with various emission reduction proposals. Much attention was given to resolving the question of whether there was significant non-linearity associated with this source/receptor relationship. At the time only anecdotal evidence existed regarding the extent or magnitude of lake acidification. Based on the available data, researchers had identified only 219 acidic lakes in the US that were likely the result of acid deposition. This estimate resulted from combining the data from a number of individual and independent studies, but it did not provide a basis for projecting either the extent or magnitude of the problem.

Similarly, as assessment teams further pursued the aquatic effects question, there was no consensus as to the basic mechanisms governing the interaction of deposition and soil to promote or prevent surface water acidification. From the perspective of the policy analyst, the ability to assess the extent and magnitude of current lake and stream damage and to project the level of future damage is essential to the development of sound policy.

Unfortunately, this line of inquiry received only limited research support. Consequently, even if the atmospheric models provided a greatly improved ability to predict deposition levels, policy makers still had only limited means to improve their ability to set policy. They still did not have a reasonable basis for deciding which parts of North America needed protection or what level of protection was required.

To address the question of the extent and magnitude of acidification, a national surface water survey was proposed. This survey was intended to be an intensive effort to sample a statistically selected population of lakes and streams from which projections would be made regarding the extent and status of acidic surface waters in the United States. Interestingly, this project received a cool reception from many aquatic researchers who viewed it as primarily a monitoring and not a research project. What was identified as central to policy development was perceived by many highly qualified scientists to be only of peripheral interest to fundamental scientific understanding.

Similar questions were raised in other effects areas such as forests and materials, where little US research was then underway. In addition, new concerns were being raised regarding the applicability of new source/receptor models to make predictions in a form usable by policy makers. It was clear that much of the acid deposition research effort needed to be modified and expanded. It was also clear that this needed to be done quickly but carefully if policy makers were to obtain timely answers while maintaining the scientific credibility of the effort.

THE RESEARCH MANAGEMENT PROCESS

The US decision to wait for more research before acting to address acid rain has been and remains controversial. Many critics have claimed that adequate information is available to make a decision and that what is needed is a multi-billion dollar expansion of the existing control program for sulphur and nitrogen oxide emissions. In light of this controversy, it was not only necessary to manage the acid rain research effort so that it addressed scientific uncertainties critical to policy analysis, but it was also necessary to conduct the research in a manner which would be recognized as scientifically objective. If research results were viewed as biased toward a particular policy or point of view, they would be of little value.

The challenge was how to involve policy analysts and policy makers in the research planning process without sacrificing the scientific objectivity of the research. To accomplish this, two separate categories of work were established. The first was the development of research questions and determination of their relative priority. The second was the design and management of individual research efforts to answer these questions. Both areas require the involvement of scientists and policy analysts. However, the policy analyst's major contribution is in the first area—developing questions and establishing priorities. In research design, the policy analyst's role is important but highly limited.

The development of research questions and priorities is an iterative process relying heavily upon the expertise of both scientists and policy analysts. The process generally begins with a review of existing scientific knowledge. This is often a major undertaking, requiring the collaboration of many scientists and some form of scientific peer review. This effort should be purely descriptive and should make no attempt either directly or indirectly to discuss what actions might be taken. Rather, it should try to describe as objectively as possible the nature of the problem. The product of such an effort is known as a "risk assessment document." Central to this assessment are a clear statement of what is known and an accounting of what is not yet understood. Since science is an inductive process, most understanding carries with it some level of uncertainty. Consequently, the risk assessment tries to convey, either qualitatively or quantitatively, the uncertainties associated with understanding.

The risk assessment document is then used by policy analysts as a basis for developing several policy alternatives. These alternatives are evaluated in terms of three primary criteria: (1) their effectiveness in solving the problem; (2) the new social, economic, or environmental problems they create; and (3) the benefits of the proposed actions compared with their costs. This inquiry is known as a "risk management analysis," and it differs substantially from the risk assessment. Although it has a scientific basis, it goes beyond science to evaluate and judge what should or should not be done.

REDIRECTING ACID RAIN RESEARCH

When risk assessment and risk management analyses were being conducted for acid rain, calculation of control benefits was extremely difficult in view of uncertainties regarding the extent and magnitude of the problem. In addition, because of uncertainties concerning source/receptor and ecosystem sensitivity, the only option providing confidence that acid deposition damage could be significantly reduced would be a major reduction in the emissions of all significant acid deposition precursors. Unfortunately, such a plan would have an extremely high social and economic cost, and in the absence of an accurate method to determine the benefit of the plan, there was no basis for comparison between benefit and cost.

The risk management analysis and the resulting clearer sense as to which information was most critical to acid rain policy development enabled policy analysts and research managers to review research priorities. Policy analysts stated their needs in very general terms and research managers responded with specific research alternatives. More often than not, questions raised by the policy analysts could not be answered directly by the research options. Consequently, policy questions were often modified somewhat to accommodate the ability of science to provide meaningful answers. Similarly, the time estimates for results offered by researchers were always longer than the policy analysts wanted, and accommodations were also sought to find ways to achieve more rapid results.

The key to the success of this kind of interactive scientific research planning has been the clear understanding of roles of each participant. Policy analysts are careful to defer to scientists on questions of science while scientists focus their attention on finding ways to meet the information needs of policy analysts.

Once research questions and priorities have been clearly identified, it is the responsibility of scientists to design, submit for peer review, and manage individual research efforts. Policy analysts generally do not become involved in this process, with two important exceptions. First, they should ensure that the final product is in a form that is understandable and is as directly usable as possible from a policy standpoint. A good scientific description of a particular phenomenon may not be directly usable by non-scientists. An extra effort needs to be made throughout the research process to ensure that the research continues to address the intended question and that the answer is ultimately expressed in a form which can be readily understood and used for policy purposes.

In addition, as new scientific results are developed, analysts can influence policy questions by either changing the priorities of ongoing research or by creating the need for new research efforts. Thus, research results need to be shared with policy analysts as they become available, and science and policy managers must collectively and regularly reassess research needs.

RESULTS OF REDIRECTION

EPA has established this process of policy research coordination to address the acid rain issue. It appears to be working. Over the past three years, several major new research initiatives have begun. The results of many of these efforts are expected in 1987. Some, like the Eastern Lake Survey, have already been completed, and their results have been made public. Publication is expected in 1987 of the results of the Western Lake Survey, the National Stream Survey, and initial findings of the Direct-Delayed Research Project, which will attempt to predict future rates of acidification. Together, these results should reduce uncertainty in the critical areas of problem definition and benefits derivable from deposition reductions. Coupled with the work in source/receptor modeling, there should be a better basis for review of the efficacy and efficiency of policy alternatives.

The full success of this effort cannot be judged for many years. However, based upon past EPA experiences, the research policy coordination process implemented for acid rain appears to be applicable to other major environmental problems such as global climate change, stratospheric ozone depletion, and indoor air quality.

Comprehensive Soviet-American Investigations of Global Atmospheric Distribution of Trace Elements and Their Potential Impact on Climate

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Interest in studying transport, transformation, and sources and sinks in the atmosphere of gaseous trace elements such as CO_2, CH_4, N_2O, and freons has arisen primarily out of concern over the near-term consequences of accumulation of these gases in the atmosphere. For this reason, two aspects of the possible consequences for the world climate from alterations in the composition of the atmosphere are under close scrutiny:

- Potential warming due to increased ambient levels of CO_2, CH_4, N_2O, and freons;
- Potential perturbation of the ozone layer as a result of discharges of freons and other gases into the atmosphere.

Mathematical models are used to evaluate potential alterations in the composition and properties of the troposphere and the stratosphere. The reliability of predictions made with the use of these models depends to a large degree on the availability of accurate information regarding transport patterns of trace elements in the atmosphere, their sources and sinks, and other factors (4,5,14,15).

Scientists conducting experimental investigations of ambient radioactive gases must therefore consider at least two approaches: large-scale experiments to determine the spatial distribution of these gases in the troposphere and stratosphere, and an ongoing monitoring program of these gases at background stations to determine accumulation rates for radioactive gases in the atmosphere (8,10,13). Joint experiments by Soviet and American scientists have tackled these two problems in recent years under Project 02.08-12, "The Impact of Air Pollution on Climate," within the framework of the US-USSR Intergovernmental Agreement on Cooperation in the Field of Environmental Protection.

In addition to land-based, airborne, and balloon-based experiments to measure ambient radioactive gases, studies using research vessels can prove extremely valuable. Meridional transects in the Pacific and Atlantic Oceans can generate nearly simultaneous ambient trace element distributions in the northern and southern hemispheres. Given that the chemical constituents of the oceanic atmosphere are controlled primarily by the ocean, it is important to make measurements directly at the surface interface. We can then evaluate gas exchange fluxes between the atmosphere and the ocean.

The use of research vessels in such experiments will yield information on the status of the atmosphere and the ocean in the measurement area. Accordingly, we have an opportunity to make more comprehensive and reliable analyses and interpretations of our findings. We can generate the most complete information by conducting specifically designed sea expeditions with a predetermined agenda. On-board experiments would involve an entire range of investigations, including measurements of trace elements, aerosols, and radiation characteristics of the atmosphere (1,2,3,6,9).

A Soviet-American experiment on gases and aerosols in the Pacific Ocean (SAGATEX-83) was conducted in 1983 on the research vessel *Akademik Korolev* provided by the USSR State Committee for Hydrometeorology. Specialists from the following research institutions participated in preparing and carrying out this series of experiments:

From the USSR: Institute of Applied Geophysics
Institute of Atmospheric Physics (Academy of Sciences of the USSR)
Main Geophysical Observatory
Far Eastern Hydrometeorological Institute
Odessa Hydrometeorological Institute
From the USA: NOAA Atmospheric Resources Laboratory
Scripps Oceanographic Institute
Oregon Research Center
University of Washington
Washington State University

The primary goals of the experiment were to investigate the distribution in the atmosphere over the ocean and the exchange between the atmosphere/ocean interface of trace elements which could potentially impact the planet's climate; to study marine aerosols; and to compare methods for measuring gaseous and aerosol trace elements.

The region for the expedition (Figure 1) and the meridional transects were selected so that we could:

- determine the latitudinal gradients of ambient trace elements;
- assess the exchange between the northern and southern hemispheres;
- investigate the impact of the intratropical convergence zone (ICZ) on atmospheric transport;
- evaluate trace element exchange fluxes between the atmosphere and the ocean;
- study the chemical makeup of current background precipitation (rain);
- compare the composition of the atmosphere in the central portion of the Pacific Ocean and the zone impacted by continental air masses;
- study the variability of optical and physico-chemical properties of marine aerosols.

The following measurements were made under the experimental program:

- Concentrations of freon-11 (F-11), freon-12 (F-12), CH_3CCl_3, CO_2, CCl_4, N_2O, CH_3Cl, CH_4, and other gases in the layer of the atmosphere closest to the surface;
- Total CO_2 and O_3 levels in the atmospheric column;

- CO_2 concentrations in the ocean's upper mixing layer;
- Spectral transparency of the atmosphere in the visible and IR ranges;
- Chemical composition of precipitation (rain);
- Radioactive tracers such as Kr^{85}, Pa^{222}, Be^{7}, and Pb^{212}.

Standard aerological, meteorological, hydrological, and hydrochemical measurements were taken for the entire expedition route. This paper presents the results of measurements taken for given trace gases in the ocean atmosphere, and findings of concomitant measurements of the partial pressure of carbon dioxide in the atmosphere and the ocean's surface layer.

Latitudinal distributions of F-12, F-11, CCl_4, methylchloroform, methane, and C_2Cl_4 in the Pacific Ocean atmosphere were recorded in the first leg of the joint expedition to Portland, Oregon (155°W, 30°S). Median trace element levels were calculated for two atmospheric blocks (30°N - 0° and 0° - 30°S) in order to quantify trace element inter-hemispheric ambient redistributions. This selection of block dimensions proved appropriate since in the first approximation it is consistent with existing views on atmospheric circulation (10). Furthermore, as Figure 1 indicates, our measurements were also made in this same latitudinal zone. Table 1 presents the results of calculations on median ambient levels of trace gases in the northern and southern hemispheres, as well as relative divergences.

All distributions obtained showed greater atmospheric trace element concentrations in the northern hemisphere than in the southern hemisphere. In addition, the non-uniformity of trace element redistribution varied between hemispheres for different trace elements. This is, above all, a function of global source and sink distribution and rates for these trace elements.

Of the above trace elements, F-12, F-11, and CCl_4 are the most long-lived; estimates put their lifetime in the atmosphere at between 50 and 80 years. The main sources for these trace elements are situated in the northern hemisphere. However, they have no effective sinks in the troposphere and break down in the stratosphere through photolytic reactions. In view of this, it is evident that the latitudinal distribution of these trace elements in the atmosphere of the Pacific Ocean is almost uniform.

Unlike F-11, F-12, and CCl_4, methane and methylchloroform

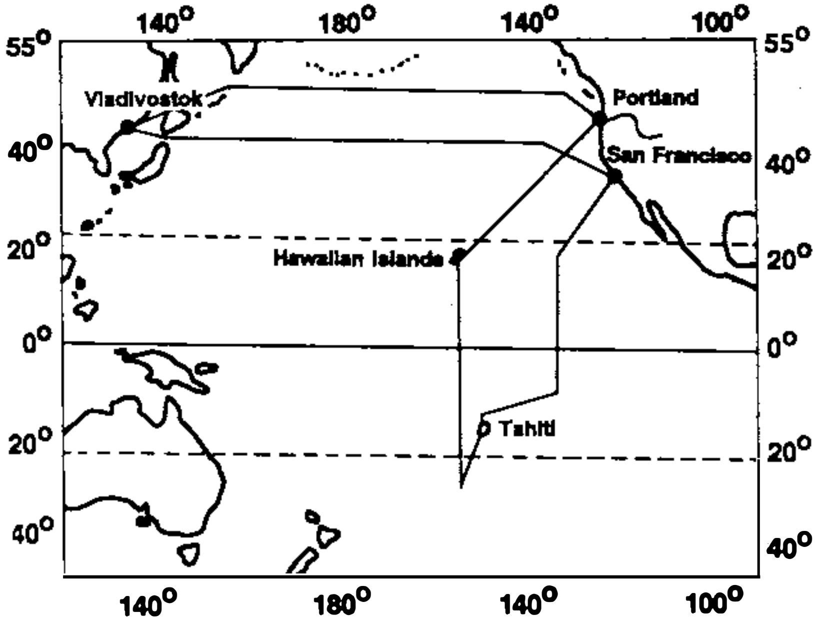

FIGURE 1 Route of 35th cruise of Soviet research vessel *Akademik Korolev.*

Table 1

Median ambient trace element levels in the northern and southern hemispheres

	Concentrations (ppt)					
Parameters	F-12	F-11	CCl_4	CH_4	CH_3CCl_4	C_2Cl_4
C_1- median concentration (30°N - O°)	350	212	170	1630	169	40
C_2- median concentration (O° - 30°S)	343	205	166	1580	130	8
C_1/C_2	1.02	1.04	1.02	1.04	1.30	5.0

are more short-lived; estimates put their lifetime in the atmosphere at between seven and 10 years. This is due to the fact that these trace elements may be removed from the troposphere by interacting with an OH radical. The global sink distribution for methane and methylchloroform are thus virtually identical. At the same time, their global sources vary. Nearly 90 percent of all methylchloroform discharges into the atmosphere occur in the northern hemisphere, while methane sources are more evenly distributed. This is the very reason why (as Table 1 demonstrates) differences between median ambient concentrations in the northern and southern hemispheres for methylchloroform are appreciably greater than for methane, totaling 30 percent and four percent, respectively.

C_2Cl_4 is the shortest-lived trace element of those measured in the experiment. Estimates put its lifetime at one-half year. Interaction with the OH radical is the basic mechanism for C_2Cl_4 removal from the troposphere. Primary sources of C_2Cl_4 input into the atmosphere are concentrated in the northern hemisphere. As can be seen in Table 1, these factors combine to result in a five-fold greater abundance of ambient C_2Cl_4 in the northern than in the southern hemisphere.

With the trace element ambient latitudinal distributions we obtained, we were able to ascertain the role of the intra-tropical convergence zones (ICZ) in inter-hemispheric trace element transport. The greatest values for the latitudinal concentration gradients were observed in the ICZ zone. It clearly follows from comparisons of the latitudinal distributions of three trace elements (F-11, methylchloroform, and C_2Cl_4) that the ICZ acts as a kind of natural barrier for atmospheric trace element transport from the northern to the southern hemisphere. As noted above, 90 percent of the sources for these trace elements are found in the northern hemisphere. Their lifetimes in the atmosphere vary considerably. They are, respectively, 80 years for F-11, seven years for methylchloroform, and one-half year for C_2Cl_4. It is evident from this that the inhibitory action of the ICZ on inter-hemispheric atmospheric transport must result in the same kinds of latitudinal distributions for F-11, methychloroform, and C_2Cl_4 that were obtained in the experiment.

Also included in the program of experiments were measurements of levels of a number of trace elements in the ocean's surface layer in order to examine the gas exchange between the ocean and

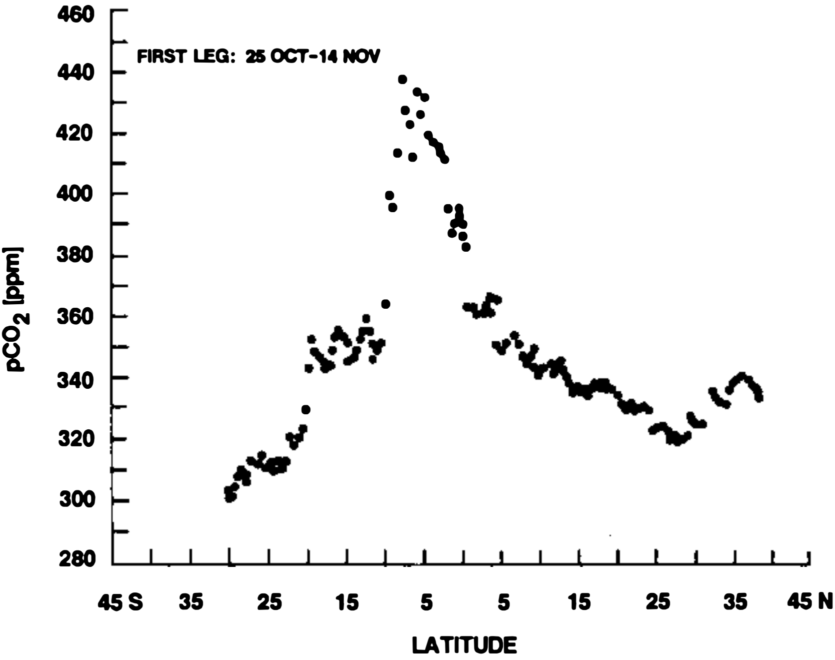

FIGURE 2 Latitudinal distribution of pCO_2 in the layer of the atmosphere closest to the surface.

the atmosphere. Figure 2 illustrates the latitudinal course of CO_2 ambient concentrations and partial pressure in the ocean's surface layer at the experiment's first stage. The difference between CO_2 ambient concentration and partial pressure in the water determines the direction of the CO_2 flux between the atmosphere and the ocean. The measurements indicated the presence of intensive CO_2 release from the ocean into the atmosphere in the Pacific Ocean's equatorial zone. It is evident from Figure 2 that this zone is situated between 5°S and 15°N, where the maximum difference of CO_2 partial pressure in the ocean's surface layer and the atmosphere reaches 110 ppm.

Calculations for pCO_2 were made at various depths (0, 20, 100, 200, and 500 meters) from data generated by hydrochemical measurements to determine the origin of equatorial zone CO_2 removal from the ocean to the atmosphere at the experiment's second stage (the cross section running along 133°W from 10°S to 20°N). Our findings point to a two-dimensional pCO_2 distribution

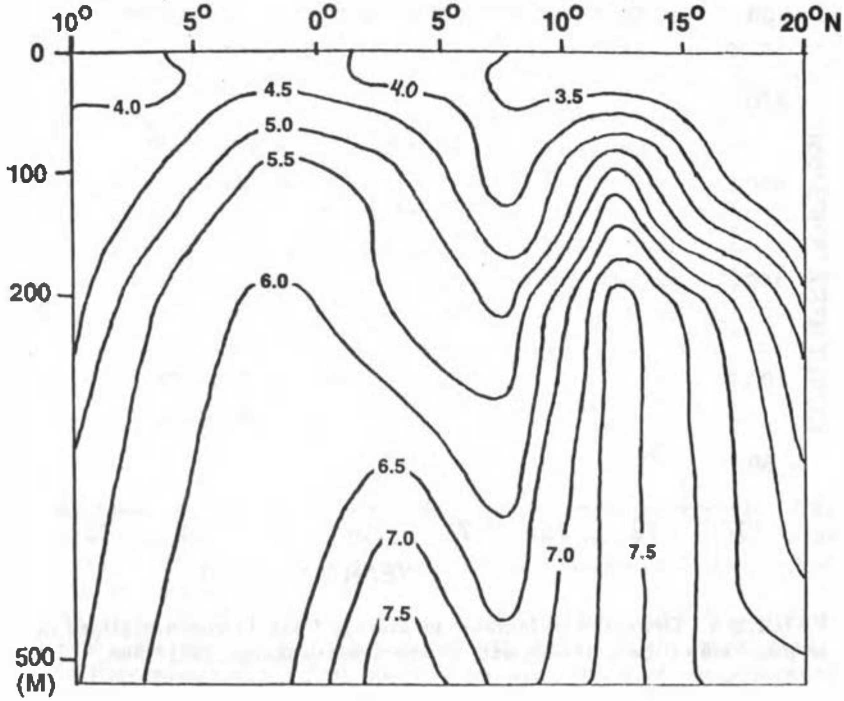

FIGURE 3 Vertical track of pCO_2 10^{-4} atmospheres in water cross section at 133° west longitude from 10° south latitude to 20° north latitude.

in the upper 500-meter layer of the ocean (Figure 3). The figure clearly indicates two zones of CO_2-enriched, ascending, interstitial water towards the surface of the ocean. This circumstance specifically explains the fact that CO_2 flux in these zones is from the ocean to the atmosphere.

With periodic on-board investigations of global, ambient trace element distribution over the ocean we can also assess temporal trends for these gases. Such studies were done by Soviet researchers in 1980, 1982, 1983, and 1986. Data yielded by these expeditions were combined with findings from investigations showing average F-11 levels in atmospheric blocks from 30°N - 0° and 0° - 30°S for 1971-79 (10). These findings generated F-11 ambient growth curves in the northern and southern hemispheres for 1971-85 (Figure 4). Figure 4 also shows that F-11 levels over the last

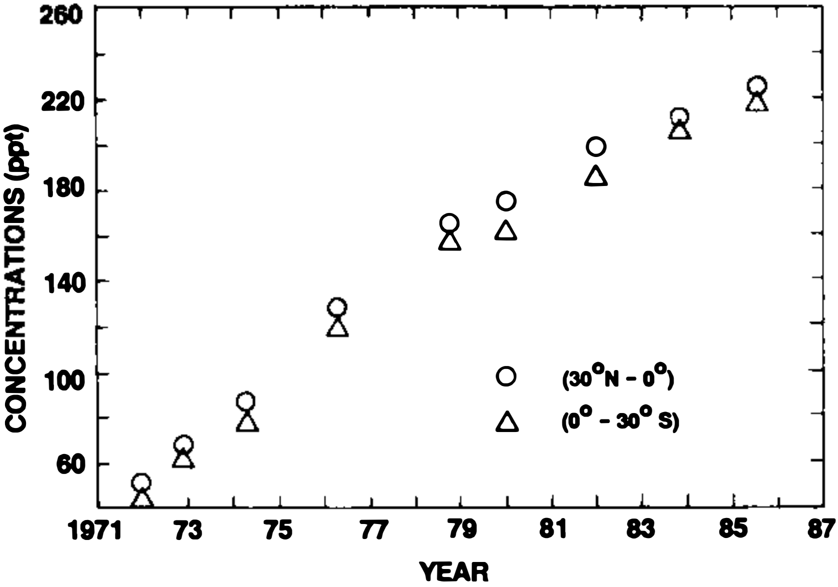

FIGURE 4 Dynamics of increase in average freon-11 concentrations in the troposphere of the northern and southern hemispheres, 1971-1986.

15 years have continued to increase, nearly quadrupling 1971 levels by 1986. Other radioactive trace elements such as CO_2, CH_4, F-12, and methylchloroform are also known to have increased during this period.

As model calculations made by Soviet and American scientists indicate, we detect a man-induced increase δT_o, with continued current growth trends δC of ambient trace element levels to 1990, when the resultant δT_o fluctuation in the mean annual temperature of the lower atmosphere in the northern hemisphere will exceed b_t by two- or three-fold (4,5). It is worth noting that CO_2 contribution here to δT_o will be less than the total contribution of the remaining gases. In other words, a situation arises when we will be able to experimentally record anthropogenic climate change due to radioactive trace element accumulation in the atmosphere. Furthermore, this modification may be considerable within several decades.

Given that our ability to take countermeasures exhibits an identical (or greater) characteristic timescale, the urgency of these problems becomes self-evident. The question then arises regarding permissible radioactive trace element emissions into the atmosphere. This is a highly complex challenge in view of the fact that we shall need to conduct a range of comprehensive investigations in the intimately linked areas of atmospheric chemistry and physics, as well as biogeochemical cycles of such substances as carbon, nitrogen, phosphorous, and sulphur (7). It is clear from this that the study of geochemical trace element cycles in the atmosphere-ocean-biosphere system is one of the most pressing problems we face in protecting the environment and in understanding climate. It is an interdisciplinary problem which calls for good coordination and mutual exchange of information.

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The Atmosphere and the Future of the Biosphere: Points of Interactive Disturbance

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THE CHANGING ATMOSPHERE

Human activity is altering the atmosphere at an increasing rate through the emission of various trace constituents. These changes are shifting both the chemical and radiative structure of the atmosphere. Among other impacts, these shifts enhance the atmospheric greenhouse effect and cause stratospheric ozone depletion. As a result, the global climate is changing and the flux of ultraviolet radiation (UV-B) to the earth's surface is increasing. Changing climate and increasing UV-B, along with other environmental stresses, affect individual plants and animals as well as entire ecosystems. However, these changes are unique because while they are not uniform, they are global in nature. Thus, they act simultaneously on ecosystems already stressed by anthropogenic effects such as air pollution on local and regional scales.

Futhermore, these global stresses—and in some cases the more local stresses—are increasing at the same rate. The stresses may be interacting synergistically, each enhancing and accelerating the effects of the others. Such synergism affects both individual ecosystems and global biogeochemical cycles. This paper discusses mechanisms for such interaction in three types of ecosystems, subject to projected atmospheric conditions of the future.

To provide a context for this discussion, Table 1 presents projections for global and regional anthropogenic N and S emissions, CO_2 concentrations, and regional surface ozone for the years 2025-30. The global surface temperature change at equilibrium and the average UV-B flux increase are also listed. The basis for these projections is given in the footnotes to the table. The equilibrium temperature corresponding to the projected trace gas changes will not actually be realized by 2030, and the size of the equilibrium change is related to the time required to achieve equilibrium.

A CLOSE LOOK AT OXIDANTS

Oxidants are of particular concern to ecosystems in the current context. Oxidants such as ozone and hydrogen peroxide can form in the presence of UV-B in both atmosphere and surface waters, and they react rapidly in chemical and biological systems. Oxidants may increase due to increased emissions of NO_x and hydrocarbons, to increased UV-B, and to higher temperatures. Although simulations of future urban ozone and hydrogen peroxide concentrations have been reported, rural or regional simulations which are critical to this study have yet to be performed. However, based on rural simulations under current conditions, a substantial surface ozone increase is projected due to the changes in the factors noted in Table 1.

Urban and rural photochemistries differ in the relative role of hydrocarbon photolysis versus ozone photolysis as a source of H_2O_2. However, urban simulations suggest order-of-magnitude changes in H_2O_2 from moderate (approximately 30 percent) stratospheric ozone depletion. The rural photochemical sequence producing H_2O_2 begins with ozone photolysis below 3200 A, so a large response to UV-B changes might be expected there as well. This argument finds support in the large seasonal H_2O_2 changes observed and latitudinal changes calculated for rural areas of industrial regions. However, in heavily polluted areas NO_x increases may somewhat reduce the increase in H_2O_2 due to enhanced UV-B, and large UV-B increases may increase H_2O_2 photolysis.

The outstanding feature of the data in Table 1 is the increase in surface ozone concentrations with a smaller concomitant increase in ambient sulphur and nitrogen oxides. The potential importance of oxidants and their relation to climate and acid rain problems have also been discussed by MacDonald.

INTERACTIVE EFFECTS OF ATMOSPHERIC CHANGE

The interactive effects of atmospheric change may be studied

Table 1

Changes in emissions and concentrations of pollutants in the atmosphere

	(1850)	1980	2025-30	
WORLD				
CO_2	(275)	340	450	ppm
δT_{eq}	--	1.0 ± 0.25	3.0 ± 1.5	°K
$\delta\Gamma$ UVB	--	0.3	18	°/o
SO_2-S *	(65)	65	205	ton S x 10^6/yr
NO_x-N *	(30)	20	65	ton N x 10^6/yr
UNITED STATES				
O_3 (rural,surface)	--	100	200	°/o
SO_2-S *	(<1)	13	17	ton S x 10^6/yr
NO_x-N *	(<1)	6	9	ton N x 10^6/yr

* Values under (1850) reflect total natural sources of atmospheric sulphur and nitrogen, not just SO_2 and NO_x. Values for later years reflect anthropogenic SO_2 and NO_x emissions.

CO_2, δT_{eq}, $\delta\Gamma_{UVB}$, SO_2-S, NO_x-N, and δO_3 refer to the atmospheric carbon dioxide concentration, equilibrium surface temperature change, ultraviolet photoabsorption rate change for O_3 at the surface, SO_2 emissions (as sulphur), NO_x emissions (as nitrogen), and change in rural surface O_3. CO_2 concentrations, and SO_2 and NO_x emissions are based on energy scenario projections which lead to a 2.4 percent per year growth rate for CO_2 emissions (Rotty and Marland 1980). A lower growth rate of 2.1 percent per year has been suggested recently by Rotty and Reister (1986). δT_{eq} is based on this CO_2 growth rate and a set of assumptions about other trace gas growth rates (Ramanathan et al. 1985). In particular, CFC-11 and -12 emissions are assumed to grow at a rate of three percent per year. The range for δT_{eq} represented a range of predictions from current models (National Research Council 1983; Hansen et al. 1983). $\delta\Gamma_{UVB}$ is based on depletions calculated by Ramanathan et al. and the photochemical rates in Whitten and Gery (1985). δO_3 was estimated from the results of photochemical smog models and from the results of Whitten and Gery from the emission rates above, with the additional assumption of hydrocarbon emissions increases similar to NO_x increases.

from three perspectives: elemental biogeochemical cycles, biophysical and biochemical processes, or ecosystems. In the category of biogeochemical cycles, for example, changes in the atmospheric-hydrospheric component of the nitrogen cycle might be examined separately, or the entire nitrogen or sulphur cycle could be examined at once. A study of biophysical and biochemical processes could specify climate-radiative (CR) and air pollution perturbation of ecosystem dynamics such as eutrophication, acidification, erosion, transpiration, and photosynthesis. An ecosystem approach could focus on changes in particular ecosystems such as freshwater lakes, estuaries, and temperate zone forests. This discussion will be organized by ecosystems.

In order to separate the problem into understandable components, three types of ecosystems have been selected. The condition of the atmosphere (including climate and radiation) in which each system will exist is then discussed, followed by an outline of how the changing atmosphere will affect the various components of the system such as soils, water, and biota. Finally, the interaction between these changes is discussed.

TEMPERATE FORESTS

The relationship of the atmosphere to the forest is determined by its impact on trees, other vegetation, surface water and groundwater, soils, microbes, and even animals. These interactions are so varied and complex that it is difficult to be definitive about the effect of atmospheric changes.

In general, higher temperature and moisture—and perhaps higher carbon dioxide concentration—increase primary productivity. Forests will also shift under stress, particularly as temperature and moisture availability change. However, temperate forests are already under stress from air pollution in both North America and Europe. A variety of symptoms of this stress are currently observed. One way to examine the effects of climate change is to project its effect on current stress mechanisms. At least five mechanisms have been proposed as causes of these symptoms, and several or all of these (and perhaps others as well) probably play a role. This section describes the proposed mechanisms and then discusses how those mechanisms would be altered by the gradual imposition of the CR changes which have been described.

Mechanisms for Anthropogenic Forest Change

The five biogeochemical mechanisms which have been proposed as contributors to forest damage are:

1. Gaseous pollutant interaction with foliage;
2. Acid precipitation or acid fog interaction with the surface of foliage;
3. Acid deposition mobilization of metals in soils and subsequent biotic-uptake and associated soil nutrient impoverishment;
4. Toxification of soils by atmospheric deposition of metals;
5. Nitrogen "overfertilization."

Visible effects include fine root damage, yellowing of conifer needles, and crown dieback. Ozone as well as sulphur and nitrogen oxides are known to be phytotoxic and may produce visible symptoms at least at the higher end of the ambient concentration spectrum. Very acidic rain can visibly damage foliage. In addition, both ozone and SO_2 may inhibit photosynthesis in the absence of short-term visible damage, which may explain the broad growth reductions inferred from tree ring data. The other mechanisms are increasingly speculative.

Gaseous pollutants are phytotoxic at levels observed near urban areas. Controlled experiments indicate that ozone, sulphur dioxide, and nitrogen oxides in combination are capable of causing visible damage to conifers. It appears that no single pollutant is capable of damaging trees at levels observed in rural areas, but combinations of these gases at low levels may act synergistically to damage trees.

As a result of anticipated atmospheric changes (Table 1), damage from gaseous pollutants could increase substantially, and the result may be non-additive should SO_2, O_3, and NO_x increase simultaneously. In addition, the suggestion by Schutt that SO_2 reduces net photosynthesis and increases vegetation vulnerability to climate extremes and insect infestation is of particular interest.

Also of concern is the potential for damage from H_2O_2. The phytotoxic properties of this chemical in droplets has been reported in Mallant and Salina, and its high solubility suggests that it may be easily absorbed by foliage. Since H_2O_2 is pervasive in atmospheric droplets and its abundance may increase several-fold under CR changes, it represents a relatively near-term threat to vegetation.

Acid precipitation or acid fog may affect foliage, either synergistically with O_2 (or H_2O_2) or separately by leaching nutrients and destroying protective coatings on conifer needles. CR changes can affect this mechanism in two ways. First, atmospheric droplets and droplets on foliage are photochemical "factories" due to internal reactions. CR changes will enhance droplet acidity by increasing photochemical activity inside and outside these droplets followed by absorption. In addition, changes in precipitation frequency will alter the surface concentration of dry deposited acids on foliage. Where dry intervals lengthen, the acid stress to leaves will increase. Conversely, drier conditions may result in lower surface wetting.

In some areas, the effect of acid deposition on soil chemistry will lead to increases in metal mobility in soil solution. Where soils are already acidic and if climate change reduces runoff, vegetation will absorb less water with lower pH and higher metal concentrations. Long-term soil nutrient impoverishment may slow where runoff decreases. However, increases in SO_2 or NO_x emissions coincident with runoff decreases could increase both nutrient loss and metal concentrations. Soil impoverishment due to acidification has already been noted in Europe, but only the most sensitive soils are seriously affected on decade timescales.

Temperature increases due to climate change can also increase soil moisture acidification. High soil temperatures lead to rapid mineralization of humus. In combination with excess nitrate deposition, this process can lead to acidic discharge of nitrates into soil solution. The associated metal mobilization may damage vegetation. Sporadic soil water acidification during warm episodes may trigger region-wide forest decline in combination with pre-existing stresses. A synergism between acid deposition and climate results because vegetation absorbs a progressively smaller fraction of available nitrogen as deposition increases. Most important, the increasing occurrence of excessively hot summers as climate changes could increase forest decline indirectly by soil acidification even when there is only a slight change in mean temperature.

Deposition of heavy metals from the atmosphere may affect vegetation, particularly in conjunction with increased mobilization due to acidification and enhanced oxidation. However, no specific link between deposited metals and observed forest decline has been proposed.

Finally, the over-fertilization of forests through excess nitrogen deposition has been proposed as a mechanism for temperate forest decline. This suggestion arose partly from test plot experiments. However, the damaging nitrogen inputs exceeded observed total nitrogen fallout in industrial regions by several-fold, so there is controversy over the importance of this mechanism. Nitrogen deposition also has been proposed as a stress on michorrhizal associations.

The discussion above notes two particularly interesting pathways for interactions among stresses on forest ecosystems: enhanced oxidant abundances interacting both chemically and biologically with other air pollutants; and increased temperature interacting with enhanced soil acid loads to leach cations and mobilize soil metals. The large increases which may occur for H_2O_2 merit special attention since investigations of the phytotoxic characteristics of this oxidant are just beginning, although synergistic responses with other pollutants seem likely. H_2O_2 and other oxidants also will accelerate the production of acids in leaf droplets. It has been suggested that doubled CO_2 levels may increase stomata resistance by as much as 40 percent, making gaseous pollutants less damaging. It is unclear whether such an argument pertains to H_2O_2 which is highly soluble. Further, ozone and perhaps H_2O_2 affect plants synergistically with acid deposition on foliage.

Increasing UV-B itself represents a significant stress on vegetation. Inhibition of photosynthesis, mutogenesis, changes in patterns of competition, and yield reductions have been observed in plants at the molecular or community levels. The interaction of these changes with climate or pollutant stresses are unknown, although it is known that increased fertilization and water stress decrease UV sensitivity. On the other hand, foliage damaged by air pollution or acid rain may be more vulnerable to UV-B.

Water availability stress in conjunction with air pollution stress has been cited as a possible cause of temperate forest decline. Climate change offers the potential for such joint interaction in areas where soil moisture is decreasing.

The foregoing discussion has identified ways in which temperature, soil moisture, nitrogen and sulphur deposition, and increased UV-B interact synergistically to stress forests. The confluence of these stresses may be expected to accelerate change and biomass reduction already observed in temperate zone forests in industrial regions, in spite of the fact that nitrogen—frequently a limiting nutrient in forests—is increasing in deposition.

Mechanisms involving oxidants and nitrogen are of particular concern. Projected increases in nitrogen emissions will in turn increase nitrogen deposition and atmospheric ozone concentrations, just as UV-B stimulates ozone production. Enchanced mineralization of nitrogen threatens to accelerate acidification and increase nitrogen leaching. Some drainage basins in the United States already discharge a large fraction of deposited nitrogen, and degradation of these systems has important downstream consequences. On the other hand, some feedbacks will be negative. Decay and nitrification may be slowed by acid conditions, and CO_2 increases may reduce pollutant interaction with foliage.

ACID SENSITIVE WATERSHEDS

CR and pollutant emission changes produce a variety of interactions which affect freshwater acidity. Among these are the direct consequences of increased sulphur and nitrogen oxide emissions and the indirect effect of changing runoff on soil water acidity. Direct increases in surface water acidity due to atmospheric CO_2 changes may also occur according to the changes in soil CO_2 saturation and the dependence of weathering on H^+ concentration changes.

A temperature-dependent soil acidification mechanism due to increased nitrification has been discussed previously. Such a mechanism indirectly affects surface waters. Acidification of lake waters may also increase due to alterations in the chemical oxidation rate in the lake water column above sediments. The anaerobic reduction of sulfate appears to be an important source of alkalinity in many softwater lakes, sometimes contributing to one-half the alkalinity. The resulting $Fe - S - H_2S$ system is highly coupled. Intervention by increasing oxidant concentrations will enhance oxidation in bioturbed sediments as well as in the overlying water column, resulting in increases in both sediment and H_2S oxidation from reduced form to sulfate. This transformation effectively reduces alkalinity and removes Fe^{+2} from the water column, making it unavailable for pyrite formation.

It appears that increasing oxidant levels resulting from UV-B and air pollutant increases may accelerate this oxidation. *In situ* oxidant formation is important in waters high in organic carbon while dissolution of oxidants from the atmosphere may be an important source in other waters. A critical question is whether oxidation kinetics are controlled by dissolved oxygen, metal catalysts, or oxidants such as O_3 and H_2O_2. Direct oxidation of H_2S by H_2O_2 becomes competitive at concentrations near 10^5M.

Such values, although an order of magnitude higher than the limited observed values, may occur in certain freshwaters now or perhaps under the scenario outlined in Table 1. More likely, intervention by H_2O_2 in the iron cycle will effectively inhibit sulphur reduction.

The net effect of such changes would be a decrease in freshwater alkalinity. Sulphur additions to waters are partly counteracted by increases in sulphur reduction rates, but rapidly increasing oxidant levels would have a countervailing effect.

COASTAL AREAS

Coastal wetlands, estuaries, and the coastal ocean will bear the brunt of the combined effects of atmospheric deposition, climate change, and enhanced UV-B. The entire physical setting in which these systems exist may change as sea level rises and erosion and salinity increase. In the long run, this process may simply eliminate many wetlands as physical systems. However, even the wetlands which survive will suffer substantial alterations in system biogeochemistry due directly or indirectly to the UV-B increase and changes in air pollutant deposition. Estuaries will be affected by wetland alteration and by a combination of radiative and chemical changes.

From the perspective of chemical inputs, the largest effects on coastal areas may arise from nitrogen loading. Nitrogen is a limiting nutrient in some estuaries and shallow ocean areas. Although internal nitrogen from phytoplankton turnover is the major nitrogen source in the coastal ocean, the annual increment from deposition and riverine input is approximately 10 percent of total nitrogen demand where upwelling is not a factor. Atmospheric deposition, along with agricultural and sewage runoff, is a major contributor to the nitrogen budgets of these waters. In the Baltic Sea, for instance, atmospheric deposition may account for one-half or more of total external nitrogen sources since nitrogen in river runoff originates partly in the atmosphere (Skulberg et al. 1984). The same situation may characterize estuaries such as the Chesapeake Bay and the Hudson River. The change in primary production as temperature and nitrogen flux from atmosphere, sewage, and agriculture increase may lead to accelerated eutrophication with algal blooms, anoxic conditions, and large-scale biotic shifts in estuaries and shallow coastal ocean areas.

Coastal waters lie at the end of a chain that begins in forested ecosystems. The changes described previously will also increase nitrogen, sulphur, and carbon flows to these waters, encouraging eutrophication and sedimentation.

Increases in UV-B may to some extent counteract this change, as UV-B is known to inhibit at least surface productivity. An important change will be the shift in plankton communities due to selective UV-B and nutrient effects. Increasing UV-B also brings along photochemical changes. Most important may be the increase in hydrogen peroxide concentration in these waters. This molecule, and the associated HO_2 radical ion, are important determinants of estuarine chemistry, including sulphur utilization and metals mobility. An increase in UV-B may change the oxidation rate in these systems. The coupling of oxidants in coastal waters with the global sulphur cycle will be discussed later.

In summary, coastal areas will be seriously disturbed by a sea level rise accompanying climate change. These shifts will be aggravated by altered drainage of freshwater to the coast. In addition, carbon, nitrogen, sulphur, and sediment additions due to upstream changes and increased deposition will combine with local temperature change to encourage eutrophication. The primary synergism probably involves the combined effect of nitrogen additions, CO_2 increases, and increased temperature on productivity. However, the systems are so interactive and the perturbations so large that singling out any one mechanism appears fruitless.

BIOGEOCHEMICAL CYCLES

The relation of climate change to the global carbon cycle has been discussed extensively, but the effects of CR changes on the sulphur and nitrogen cycles have not been discussed. Some of these changes have already been noted. Table 1 illustrates the future dominance of global anthropogenic sources of sulphur and nitrogen over natural ones.

Sulphur is the easiest cycle to discuss because it is dependent upon the other cycles. However, the potential for global regulation of the other cycles which influence the sulphur cycle is limited. The sulphur cycle is already seriously disturbed on a regional scale by atmospheric deposition, leading to sulfate accumulation and acidification in soils and surface water.

It is less well understood that CR changes may affect the sulphur cycle. For instance, the sulphur emission rates of soils (as CS_2 and OCS) may be strongly dependent on temperature, varying by two-fold or more for a 5° Centigrade change (Adams et al. 1981). The increasing anthropogenic sulphur load—now roughly equal to natural emissions—also may cause increased biotic emissions of reduced sulphur from soils. OCS is the major source of the stratospheric sulfates which scatter sunlight, so such changes can affect both surface and stratospheric climate. Freshwater H_2S emissions may also increase as temperature and redox balances are altered, shifting the disposition of sulphur runoff from pyrite to gaseous form. However, this sulphur may be re-oxidized due to enhanced oxidant levels.

The largest biological effect of sulphur cycle alteration may be associated with increased acidification caused by loss of alkalinity from net sulphur reduction in acid sensitive waters. Sulphur emissions from coastal wetlands may increase due to eutrophication and increased sedimentation, but wetland losses and increased oxidant levels will counteract this change. In any case, parts of the global sulphur cycle will be greatly disturbed.

Another important question relates to CR effects on ocean microbes which reduce sulfates in sea salt (Charleson et al. 1986). If these species control fine aerosol concentrations and droplet nucleation, both UV-B and temperature changes could alter global weather since the microbial reduction rate is bound to be affected.

The perturbation of the nitrogen cycle by CR changes is less straightforward than the sulphur/CR relationship. Enhanced nitrogen deposition and CO_2 may synergistically alter primary production which will in turn affect the nitrogen cycle. The nitrogen cycle has already been altered both globally and regionally with anthropogenic inputs comparable to or greater than natural inputs for rivers and the atmosphere. In remote forests, internal sources are 10–30 times greater than inputs and outputs. However, in temperate forests in industrial regions nitrogen uptake accounts for about 50–60 kg NO_3 per hectare year, while only 45 kg per hectare year are cycled internally. Deposition is as high as 50–100 kilograms at higher elevations and 10–20 kilograms at low elevations. Thus, nitrogen deposition plays an important role in determining output due to the large leaching that occurs in some forests.

Although oceans have a substantial nitrogen reserve, the anthropogenic input is currently within a factor of two of other inputs when both direct deposition to the ocean surface and the anthropogenic component of river runoff are considered. For the ocean as a whole, these inputs are only about one percent of annual nitrogen requirements and are small when compared to the internal pool. However, in estuaries, coastal regions, and relatively enclosed seas such as the Baltic, anthropogenic nitrogen input may be large when compared to the local reservoir, leading to eutrophication.

How will CR changes affect the nitrogen cycle? First, coastal primary production will increase as temperature, CO_2 concentration, and nitrogen flux increase (with increasing deposition and runoff from sewage, agriculture, and degrading forests). This change is more than additive. Second, terrestrial systems respond to disturbance by increasing respiration relative to primary production as well as by increasing nitrogen leaching. Such changes have been monitored in detail in response to clear cutting. They also may be expected to occur in response to a relatively rapid and continuous climate change where the rate of change will far exceed normal migration rates for forests. Therefore, disturbance by either air pollution, climate, or other factors may be expected to accelerate nitrogen mineralization and flux—and perhaps phosphorous flux—from terrestrial systems. Of course, such releases are self-limiting, either by loss of the terrestrial nitrogen pool or by forest recovery, if any, after disturbance ceases.

In conclusion, the nitrogen cycle is already disturbed by anthropogenic inputs for terrestrial systems. For temperate forests in industrial areas, deposition far exceeds fixation and may even rival internal sources in some cases. For oceans, anthropogenic nitrogen may be important in estuaries, coastal areas, and partly enclosed seas. The nitrogen cycle in both cases is strongly affected by temperature, so that CR changes along with nitrogen emissions increases will seriously disturb the nitrogen cycle for terrestrial and certain salt water ecosystems. How UV-B increases affect both algal blooms and nitrogen-cycling bacteria is for the most part unknown.

ECOSYSTEMS IN THE FUTURE

Changes in climate-radiative and pollutant characteristics of the atmosphere may substantially alter ecosystems and biogeochemical cycles by the middle of the next century. With regard to biogeochemical cycles, changes in temperature and oxidant levels will generally accelerate the loss of carbon, sulphur, and nitrogen from terrestrial reservoirs. The most prominent concern is the effect of increased levels of atmospheric oxidants. Increased oxidants will:

- Interfere in the sulphur cycle, increasing freshwater acidification;
- Increase solubility and mobilization of some metals;
- Act as a phytotoxin;
- Indirectly enhance nitrogen mineralization and loss from forests due to the degrading consequences of phytotoxicity;
- Enhance carbon and nitrogen respiration from soils by accelerating decomposition;
- Enhance sediment oxidation, as is the case with increased nitrates and sulfates.

Ecosystem disturbance from climate change will also increase soil carbon respiration. Respiration will exceed production due to the long equilibriation time for terrestrial systems, and forests may experience decline. It is likely that nitrogen loss will increase with respiration due to climate disturbance since nitrate fluxes increase markedly in disturbed forests. Mineralization will accelerate in the warmer, wetter soils brought about by forest decline and in some areas directly by climate change.

On the other hand, ocean surface flora experiencing a nitrogen surge from these changes and from direct deposition equilibriate rapidly. They may respond to these changes with increased productivity, leading to local coastal eutrophication as production shifts from land to sea, particularly near industrial regions. This productivity may also accelerate ocean sulphur release by shifting to anoxic conditions. Over a much longer period, this process can again withdraw substantial carbon from the atmosphere. Biota on land and in the sea which are needed as a carbon reservoir may experience a net decline in the short term.

To some extent, these changes occur synergistically, and several specific mechanisms have been proposed to illustrate these synergisms. Climate and UV-B changes fit into a pattern of preexisting disturbances, the effects of which will be accelerated. The overall conclusion, therefore, is that those interactive changes may move nutrients from land to sea, increasing biota at sea but sharply decreasing them on land.

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Microbiological Components of Sulphur and Carbon Cycles in the Ocean

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Three features in the physiology of microorganisms determine their key role in cycling matter in nature. First of all, microorganisms are producers of unique enzyme systems which allow them to use a broad diversity of mineral and organic compounds in their metabolism. Microorganisms involved in the sulphur cycle not only utilize the most diverse organic sulphur compounds but also use hydrogen sulfide, natural sulphur, sulfides, sulfates, and other oxidized sulphur compounds in the exchange. Carbon cycle microorganisms exhibit an equally wide range of physiological requirements. Some of these intensively utilize gaseous carbon compounds (carbon and methane oxide and dioxide); others rely on aqueous or solid hydrocarbons; and a third group breaks down complex biopolymers such as chitin, cellulose, and lignin.

The second physiological property of microorganisms which ensures their wide distribution in nature is their unique adaptability to extreme conditions in the surrounding environment. Microorganisms hold all the records among living organisms for resistance to acids and alkalines, high and low temperatures and pressures, increased salt concentrations, and high radiation dosages. Furthermore, many specialized groups of microorganisms such as obligate thermophiles, barophiles, halophiles, and acidophiles not only withstand temperature or pressure extremes and high concentrations of salts or acids, but they are incapable of developing under normal physical and chemical conditions.

The third and final geochemically significant physiological feature of microorganisms is their ability to make a rapid transition from an inactive, "dormant" condition to intensive reproduction and consumption of the substrata within their sphere of vital activity.

While marine biologists until quite recently conducted their research independently of the work of geochemists, oceanographers, and ecologists, much attention was focused on studying the diversity of microorganism life forms in the ocean's water column and bottom sediments. At the same time, due to the widespread use of physical and chemical methods over the last two decades, scientists began to quantify the contribution of microorganisms in the cycles of various elements in the oceans.

The primary aim of this paper is to quantify certain microorganism-induced processes at play in sulphur and carbon cycles in bottom sediments of the world's oceans. The factual material was compiled by microbiologists of the Academy of Sciences of the USSR during the past 12 years in the course of comprehensive oceanographic expeditions on research vessels provided by the Academy of Sciences and the USSR State Committee for Hydrometeorology and Control of the Natural Environment. These studies were conducted in the Pacific and Indian Oceans and in the Baltic, Black, Caspian, and Okhotsk Seas.

Bottom sediment samples were obtained at depths of up to roughly 100 meters from the water/silt interface by using bottom samplers and geological tubes and by conducting exploratory and mapping drilling from special drilling vessels. In addition to microbiological analyses, we studied anaerobic cellulose decomposition rates, methane formation and oxidation, and hydrogen sulfide and sulfide formation during microbiological sulfate reduction in silt water. Radioactive and stable sulphur and carbon isotopes were widely used to study the rates of microbiological processes in bottom sediments. All of our microbiological and geochemical experiments were conducted in laboratories on our research vessels, using fresh, natural material immediately after sampling the water and bottom silt.

The process of microbiological sulfate reduction was studied in the greatest detail. Sulfate reduces to hydrogen sulfide while organic carbon is concurrently anaerobically oxidized to CO_2. The vertical distribution of sulfate reduction in the silt column varies significantly. We find it in the uppermost layer in near-coastal silt where its greatest value is at a depth of 5–15 centimeters. Reduction diminishes as sulfate is depleted with increasing depth.

In less organic-rich sediment of the continental slope and base, the intensive process of sulfate reduction begins at the subsurficial layers of bottom sediments underneath the layer of oxidized silt. The thickness of this silt sometimes reaches several meters.

This anaerobic process takes place in virtually all of the sediments on the shelf, on the continental slope, and at the foot of the continental slope. However, the rate of this process fluctuates within a very broad range. In near-coastal, organic-rich sediment it reaches a level of tens of milligrams of hydrogen sulfide per kilogram of raw silt per day. This rate drops to no more than several tenths of a microgram per kilogram of silt diurnally for sediment in the open ocean.

Having obtained extensive factual material on sulfate reduction rates in different regions of the world's oceans, we were able to calculate the total annual production of microbial hydrogen sulfide in bottom sediment. This value is 495 million tons of sulphur per year. Approximately 100 million tons of sulphur from this total are buried every year in bottom sediment while the remaining 395 million tons of hydrogen sulfide are re-oxidized to sulfate in the uppermost silt layers or in near-bottom water layers. A relatively insignificant portion of hydrogen sulfide of microbiological origins—approximately several million tons annually—enters the atmosphere from shallow-water sediment.

Our quantification of sulfate reduction is interesting not only for a balance assessment of the sulphur cycle but also in terms of calculating conjugate cycles of elements, primarily carbon and oxygen. Suffice it to say that at least 375 million tons of organic carbon would have to be expended to form 495 million tons of sulphur sulfate in sulfate reduction. Approximately 0.9 billion tons of dissolved oxygen would be required to oxidize 395 million tons of surplus hydrogen sulfide.

An in-depth study of the isotope composition of reduced and oxidized sulphur compounds found in ocean sediments was conducted in parallel with our microbiological investigations. This study demonstrated that the isotope composition of hydrogen sulfide and other reduced sulphur compounds is primarily coupled with sulfate reduction rates: the lower the rate, the more hydrogen sulfide will become enriched with light sulphur 32.

We also used a similar methodological approach to study a second, very important, anaerobic process: microbial methane formation. Since different methane-producing bacteria can produce methane either by reducing carbonic acid or from methyl groups of organic acids, we used CO_2 and acetate tagged with carbon 14 to determine the rate of methane formation. Like sulfate reduction, the rate of microbial methane formation in ocean sediments varied within rather wide ranges. However, unlike sulfate reduction, the rate of methane production remained at approximately the same level for the entire cross section of reduced sediments that we studied. In a number of instances, it even increased at a depth of 2–3 meters from the surface of the silt/water interface.

On the basis of a comparison of our microbiological data with findings on isotope analyses of methane and carbonic acid (published by I. Kaplan), we can hypothesize that the processes of microbiological methane formation in the ocean's bottom sediment occur in the sediment column, which is measured in tens or even several hundreds of meters. Under these conditions, the yearly production of microbial methane in the upper two meters of the column of sediment alone amounts to the quite substantial figure of approximately 325 million tons of methane. Since a minimum of two moles of organic carbon are expended to produce one mole of methane, it becomes clear that the process of microbial methane production in sediment also accounts for a significant portion of organic carbon consumption in early diagenesis in ocean sediments.

Microbial methane in the ocean's bottom sediments undergoes various fates. In ocean sediments of cold and temperate climates at depths of more than 500 meters, this methane might accumulate as crystalline hydrates and form natural gas deposits. A portion of the methane degases from shallow-water sediments (particularly in regions with a hotter climate) into the water column and the atmosphere, thereby contributing to the formation of the atmosphere's methane pool. Finally, part of the microbial methane in the upper silt layers undergoes oxidation with aerobic methane-oxidizing microorganisms.

The possibility of oxidizing methane in anaerobic conditions using microorganisms has been sharply debated in the oceanographic literature. Although we have yet to identify which distinct organisms are capable of performing this process, we have no doubt regarding anaerobic methane oxidation in sediment. We have been able to confirm this by conducting experiments with radioactively tagged methane in studies on anaerobic sediments of several lakes and the Black and Bering Seas. Our data show that about 30 percent of the methane produced by the activity of methane-forming bacteria in sediment is re-oxidized in anaerobic conditions in these same sediments.

Aerobic mineralization of organic matter in the ocean's bottom sediments has thus far been studied in much less detail. Current data on the distribution of aerobic saprophites and aerobic cellulose-decomposing bacteria quite clearly indicate that the maximum number of aerobic bacteria is found in the surficial layers of near-coastal, organic-rich sediments. The abundance of these microorganisms drops sharply as distance from the shoreline increases and samples are taken deeper in the silt column. Findings from studies of oxygen consumption rates in ocean bottom sediment can give an approximate picture of their geochemical activity. In 1983, B. Jorlensen estimated that the total oxygen consumption by bottom sediment in the world's oceans equals approximately six billion tons of oxygen per year. If we subtract from this figure 900 million tons of oxygen reacting with surplus hydrogen sulfide, the remaining five billion tons of oxygen are used to aerobically oxidize organic matter.

From Redorild's formula we know that 138 moles of oxygen are used to produce 106 moles of organic carbon in the oxidation of planktonogenic organic matter. It follows from this that approximately 1.4 billion tons of organic carbon are oxidized annually in aerobic conditions of the upper layers of the ocean's bottom sediment. If we now add to this figure the amount of organic carbon used for sulfate reduction and methane production (which is in excess of one billion tons of organic carbon per year), we can conclude that the minimum flux of organic carbon from the ocean's water column to its bottom sediment should be 2.5 billion tons of organic carbon per year. This represents from five to 10 percent of the total value of primary production of organic matter in the ocean.

In connection with the aforementioned figures, it is also interesting to note that many global carbon cycle models which were constructed without consideration of large-scale geochemical activity of microorganisms in the ocean's bottom sediments have provided estimates that the flow of organic carbon into bottom sediment is 20–25 times less than the value which incorporates the latest data for rates of aerobic and anaerobic sulphur and carbon cycles in the ocean's bottom sediment.

Potential Impacts of Global Climate Change on the Environment

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Since Tyndall's experiments in 1862, researchers have known that atmospheric gases can alter the earth's radiative balance, and they have recognized that carbon dioxide and other radiative trace gases may affect the global climate. During the last year, as a result of the UNEP/WMO/ICSU meeting in Villach, a renewed interest in the global climate has been sparked in the US Congress, in various government agencies, and in the press. Indeed, the warning in the Villach report states:

> As the result of the increasing concentrations of greenhouse gases, it is now believed that in the first half of the next century a rise of global mean temperature could occur which is greater than any in man's history ... (T)here is little doubt that a future change in climate of the order of magnitude [now projected] ... could have profound effects on global ecosystems, agriculture, water resources, and sea ice (WMO et al. 1985).

This warning has provoked many scientists to ask: How can the environmental and health risks of man-induced changes in the global atmosphere be assessed? Within the US Environmental Protection Agency (EPA), there is recognition that conducting risk assessments is an inherently difficult undertaking which is usually limited by scientific knowledge and data. The process works best when risks can be readily quantified or expressed in defensible numerical form.

For chemical hazards—emissions in the air, effluents discharged into the water, leaks from hazardous waste landfills, or applications or pesticides—risk assessment can work rather well although it may be slow and costly. Risk assessment is most particularly geared toward assessing cancer and other health risks. In this regard, EPA has established sophisticated procedures to arrive at a final estimate of risk reduction due to regulation. Basically, this risk reduction estimate is a multiplicative function of three estimates: the reduction in emissions due to regulation × the level of risk per unit of emissions × the level of risk per unit of exposure. In recent years, EPA has expanded its risk assessment focus to include larger, regional problems such as acid rain.

Unfortunately, the prospect of a global warming presents us with a larger, more complicated, and less manageable problem. Estimating a dose/response relationship for the effects of climate change on the biosphere is simply not possible. Unlike the chemical hazards that normally occupy EPA's agenda, global warming represents an alteration in the thermal radiation balance of the planet. As more heat is trapped in the earth's atmosphere, entire ecological systems will be affected: oceans, forests, soils, hydrology, and agriculture. The time and space dimensions of these problems go beyond other environmental problems—beyond even the scope of regional or subcontinental problems such as acid rain. The impacts of climate change are irreversible within the next several decades, cover the entire globe, and have the potential to be substantially different from any other impacts in man's history.

This all-encompassing nature of climate change presents a situation where only pieces of the puzzle can be examined. EPA, along with other US agencies and agencies in other countries, is collecting early bits of information—both qualitative and quantitative—regarding the predicted impacts of climate change on various systems of the biosphere. What emerges are glimpses of information that give some idea of the risks associated with an unmitigated global warming.

These studies assume that warming will take place gradually, and there is some evidence that climate has not always followed such a path. In fact, natural systems including climate may absorb stresses for long periods of time without much outward sign of damage. There may be "jump events" or "thresholds" where conditions rapidly deteriorate. Consequently, climate warming and its effects on ecosystems may not proceed in a smooth, incremental fashion, but instead may exhibit large jumps. Thus far, however, the possibility of these threshold events has not been factored into climate change analyses.

Clearly, much research remains to be done. Recognizing these limitations, this paper summarizes what is known about climate impacts on the environment with emphasis on sea level rise, forests, agriculture, water resources, and human health. Many of the conclusions are drawn from a comprehensive summary recently prepared by EPA (1986).

SEA LEVEL RISE

One of the most widely examined impacts of the projected global warming is a possible rise in sea level. Researchers have identified at least three mechanisms which might cause a significant rise: the warming and resulting expansion of the upper layers of the ocean; the melting of alpine glaciers; and the melting and disintegration of polar ice sheets in Greenland and Antarctica. In the absence of any efforts to limit global warming, estimates of the rise in sea level by the year 2100 range from 50 centimeters to over two meters. Even the most conservative estimate implies a substantial acceleration over the 10 to 15 centimeter rise of the last century.

A rise in sea level in such a range would permanently inundate wetlands and lowlands, accelerate coastal erosion, exacerbate coastal flooding, and increase the salinity of estuaries and aquifers. Although wetlands have kept pace with sea level rise in the last several thousand years, a one or two meter rise would destroy a majority of US coastal marshes and swamps. River deltas such as those of the Mississippi, the Ganges, and the Nile appear to be particularly vulnerable.

Along the open coast, beach erosion could reach one to two meters for every centimeter rise in sea level, in addition to whatever erosion might be caused by other factors. Because buildings are generally found within 50 meters of the shore, even the 20 centimeter rise projected for the next 40 years could threaten coastal property and the recreational use of beaches, unless additional remedial measures are implemented.

Sea level rise would also increase the vulnerability of coastal areas to flooding from storm surges and rainwater. In the area of Charleston, South Carolina, for example, the area now flooded by a 100-year storm would be flooded by a 10-year storm if sea level rises 1.6 meters. Protection against increased flooding would require improvement or construction of levees, seawalls, and drainage facilities.

Higher water levels would also increase the salinity of estuaries and aquifiers. Philadelphia's drinking water intakes on the Delaware River would be threatened by a rise of less than one meter, as would adjacent aquifers in New Jersey that are recharged by the currently fresh part of the river. Construction of additional reservoirs might be necessary to offset salinity increases.

Few studies have estimated the economic significance of future sea level rise. In the United States, an estimate of the potential nationwide cost of defending shorelines and other resources has not yet been made.

FORESTS AND NATURAL VEGETATION

Forests, the most abundant and important vegetation type on land, serve an integral role in the world's ecological and climatological system, covering 35 to 40 percent of the earth's surface, producing 65 percent of the annual carbon fixation (net primary productivity), and storing over 80 percent of the world's organic carbon. Ecologically and economically, forests serve a number of purposes: they help protect the quality of streams and groundwater supplies; prevent soil erosion; provide fuelwood, timber, paper, chemicals, and other forest products; constitute a home for wildlife; and serve as a recreation area for millions of people.

Globally, the areal extent of forests has been shrinking since pre-agricultural times as deforestation rates have exceeded rates of reforestation. This reduced supply, coupled with expected increases in global demand for wood, may result in critical wood shortages by the end of this century. In addition, deforestation poses enormous ecological and climatological consequences. Loss of forests usually implies some hydrological damage as well as increased soil erosion. Climatologically, deforestation—which causes a net release of carbon into the atmosphere—may make a significant contribution to global warming.

These close associations between human populations and the terrestial biosphere impel us to consider how climate change affects natural vegetation, and how natural vegetation, in turn, influences global climate. The paleo-vegetational record can yield useful insights into these processes. It shows that climate change as large as that expected to occur—in response to a doubling of CO_2 concentrations or equivalent radiative impacts from other trace gases—is likely to induce significant changes in the composition and patterns of the world's biomass.

Changes of two to four degrees Centigrade have been significant enough to alter the composition of biomes, causing new biomes to appear and others to disappear. At 18,000 years before the present, eastern North American vegetation was quite distinct from that of the present day. The cold and dry climate of the time seemed to have precluded, for example, the widespread growth of many species such as birch and hemlock which are fairly abundant in present-day forests.

Limited experiments with dynamic vegetation models which produce time-dependent estimates of the magnitude and pattern of individual plant taxa responses to climate change suggest that decreases in net biomass may occur in North America and that significant changes in species composition are likely. Experiments with one model by Solomon suggest that eastern North American biomass may be reduced by 11 megagrams per hectare (10 percent of live biomass), given the equivalent of a doubled CO_2 environment.

Such changes in natural growing conditions may affect future forest management decisions. One study shows, for example, that loblolly pine populations are likely to move to the north and northeast into Pennsylvania and New Jersey, while its range shrinks in the west. The total geographic range of the species may increase, but a net loss in economic productivity may result because of shifts of less accessible and less productive sites. While the extent of such changes is unclear, adjustments will be needed in forest technology, resource allocation, planning, tree breeding programs, and decision-making to maintain and increase productivity.

In order to make predictions which are detailed enough to influence future decision-making, models must be developed, improved, and validated for all major kinds of vegetation. They should eventually incorporate the joint effects of atmospheric CO_2 increases, other air pollution effects, and possible increases in ultraviolet (UV) radiation. Improved estimates of future regional climates are also required in order to make accurate predictions of future vegetation change. Finally, a concern shared with colleagues in the USSR is the fate of the boreal forest and tundra if increased temperatures occur in polar regions.

IMPACTS ON AGRICULTURE

Historically, climate has had a profound influence on farm productivity and the geographic distribution of crops. Examples include the 1983 drought in the United States, which contributed to a near 30 percent reduction in corn yields; the persistent Great Plains drought in the United States between 1932 and 1937, which contributed to nearly 200,000 farm bankruptcies; and the climate shift of the Little Ice Age (1500 to 1800 A.D.), which led to the abandonment of agricultural settlements in Scotland and Norway.

Changes in climate as a result of trace gas-induced warming are likely to affect world agriculture. In addition to the direct effects of elevated temperatures, effects are likely from changes in other climatic and hydrological variables such as precipitation and runoff. These effects will extend from local to regional and international levels.

The main effects likely to occur at the field level will be physical impacts of changes in thermal regimes, water conditions, and pest infestations. High temperatures have caused direct damage to crops such as wheat and corn. Moisture stress often associated with elevated temperatures is harmful to corn, soybean, and wheat during flowering and grain fill. Increased pest infestation is often associated with higher temperatures.

Even relatively small increases in mean temperature can greatly influence the probability of extreme climatic events. Analysis of historical data has shown that an increase of 1.7° Centigrade in mean temperature for a city like Des Moines, Iowa, increases by about a factor of three the likelihood of a maximum temperature during five consecutive days of at least 35° Centigrade. In regions where crops are grown close to their maximum tolerance limits, changes in extreme temperatures may have significant effects on crop growth and yield.

Limited experiments using climate scenarios and agricultural productivity models have demonstrated the sensitivity of the agricultural systems to climate change. Future farm yields are likely to be affected by climate because of changes in the length of the growing season, heating units, extreme winter temperatures, precipitation, and evaporative demand. In addition, experiments show that total productivity is a function of the availability of land, the location of soil and water resources, the ability of farmers to shift to different crops, and agricultural trade regulations.

Accommodating to climate change may require shifting to new lands, creating support services and industries, improving and relocating irrigation systems, developing new soil management and pest control programs, and breeding and introducing new heat- or drought-tolerant species. The consequences of these decisions on the total quantity, quality, and cost of food are difficult to predict.

However, methods for studying climate change and agriculture are improving as climate, crop growth, and economic models continue to be developed. Studies of transient, rather than equilibrium, climate and its effects should be emphasized, as should the impact of changes on the frequency of extreme events. As the atmospheric models improve, impact studies should be repeated and expanded to include testing of possible responses to the potential effects. In this way, improved information will be available for future policy decisions.

CHANGES IN WATER RESOURCES

All natural hydrological processes—precipitation, infiltration, storage and movement of soil moisture, surface and subsurface runoff, recharge of groundwater, and evapotranspiration—are affected by climate. The inextricable links between the water cycle and climate ensure that potential climate change will significantly alter hydrological processes throughout the world.

Strong evidence of these climate/hydrology links is provided by paleological evidence. Although the number of present-day lakes is broadly comparable with the number which existed during the last ice age (18,000 years ago), climate change since that time has significantly altered the location of lakes. For example, there is evidence that indicates the existence of many tropical lakes and swamps in the Sahara, Arabian, and Thor deserts about 9,000 to 8,000 years ago.

As a result of changes in key hydrological variables such as precipitation, evaporation, soil moisture, and runoff, climate change is expected to have significant effects on water availability. For many aspects of water resources—including human consumption, agricultural supply, flooding and drought management, groundwater use, recharge, and reservoir design and operation—these hydrological changes will have serious implications. In Canada, it has been demonstrated that, based on model results, net basin supply will decrease in the Great Lakes with associated impacts on

	GISS	GFDL
Temperature Change	+4.3 to +4.8 C	+3.1 to +3.7 C
Precipitation	+6.4%	+0.8%
Actual Evapotranspiration	+18.1%	+6.7%
Snowmelt	−45.9%	−35.8%
Runoff	−10.9%	−8.2%
Soil Moisture Deficit (summer)	+116.4%	+166.2%
Net Basin Supply (normal winds)	−20.8%	−18.4%
Net Basin Supply–Consumptive Use (2035 proj.)	−28.9%	−26.4%
Net Basin Supply (80% winds)	−4.1%	−4.0%
Net Basin Supply–Consumptive Use (2035 proj.)	−11.8%	−11.7%

Reference: Stewart J. Cohen, Canadian Climate Center, 1985

FIGURE 1 Effects of climatic change scenarios on annual water balance of the Great Lakes basin.

many sectors (Figure 1). Similarly, examination of the predicted results from several general circulation models shows similarities in summer soil moisture and winter runoff for California (Figure 2).

HUMAN HEALTH CONCERNS

Weather has a profound effect on human health and well-being. In particular, climatic extremes such as heat and cold waves have been linked to increases in mortality. For example, it is estimated that in the United States the 1980 heat wave contributed to over 1,300 fatalities. If change induced by trace gases alters the probability of extreme events, as GCM results now indicate, future increases in weather-related mortality may occur.

In one case study, which has not accounted for the effects of air pollution, a 7° Farenheit warming in New York City was estimated to increase total summertime mortality by more than 3,200 deaths per year (Table 1). If, however, New Yorkers gradually adjusted their behavior and acclimatized to the hotter weather, mortality

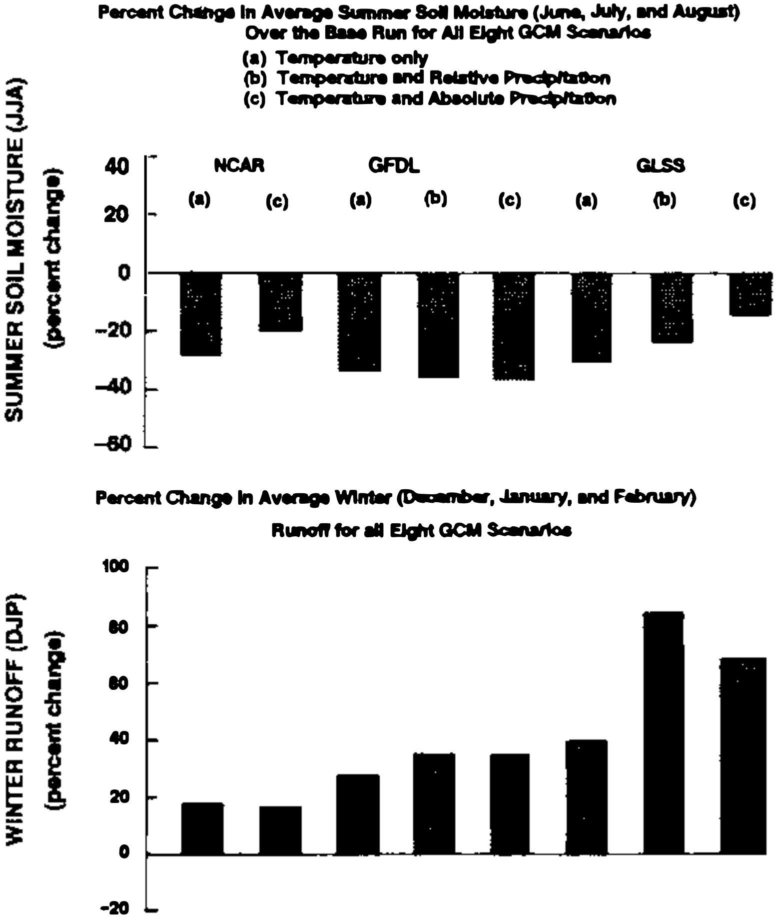

FIGURE 2 Percent change in average summer soil moisture (June, July, and August) over the base run for eight GCM scenarios: (a) = temperature only; (b) = temperature and relative precipitation; (c) = temperature and absolute precipitation. [bottom] Percent change in average winter runoff (December, January, and February) for eight GCM scenarios.

might not increase at all. It is hypothesized that if climate warming occurs, some additional deaths would likely occur because of a lag in perceptions and because the basic infrastructure of the city would prohibit full and timely acclimatization.

Table 1

Average monthly increase in total mortality for various warming scenarios in New York

	Degrees above present					
Month	0	1	2	4	5	7
No Acclimatization						
June	19 (45)	34 (81)	57 (136)	114 (273)	156 (373)	253 (605)
July	86 (206)	110 (263)	154 (368)	282 (674)	372 (890)	622 (1488)
August	25 (60)	37 (88)	64 (153)	170 (407)	250 (598)	487 (1165)
TOTAL	130 (311)	181 (432)	276 (657)	566 (1354)	778 (1861)	1362 (3258)
Full Acclimatisation						
June	19 (45)	33 (79)	32 (77)	5 (12)	0	0
July	86 (206)	62 (148)	54 (129)	11 (26)	0	0
August	25 (60)	29 (69)	55 (132)	4 (10)	0	0
TOTAL	130 (311)	124 (296)	141 (338)	20 (48)	0	0

Note: Numbers in parentheses represent raw, unstandardised mortality estimates. They are calculated by multiplying the standardised values by 2.39. The population of the New York metropolitan area in 1980 was 9,120,000, which is 2.39 times the population of the standardised city (3,811,000). These values are not adjusted for potential future population increases.

SUMMARY

The important task of estimating the risks to the environment of the United States from global climate change in the next century has only begun. There are no precedents or analogs to help with predictions. A comprehensive quantitative analysis has not been attempted and may never be possible given the complexity and interactive nature of the biosphere. Moreover, the chemistry of the atmosphere in the next century—in the form of acid rain and tropospheric ozone—will also be different and the amount of UV-B radiation may be altered by changes in stratospheric ozone. Hence, a complete understanding of the risks to the environment in the next century will need to consider these synergistic impacts as well as changes in global climate.

A better understanding of the environmental effects of global climate change can be gained by using and improving the risk assessment methodologies currently available. Risk assessments may have to be constantly revised as new scientific information becomes available, and the ultimate answers will take years of work. The joint US-USSR project to examine assessment methodologies under Working Group VIII of the intergovernmental environmental agreement is an important first step. It will assure that the risks of global climate change to the environment are understood in both countries.

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Assessing the Global Effects of Insecticide Use on Ecosystem Stability

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Investigation of the mechanisms providing stability of the biosphere and its components is an urgent problem for theoretical physics. This problem also holds practical significance since identifying man-induced instability is possible only with exact knowledge of natural mechanisms and the weak points of corresponding natural processes. This circumstance makes the problem of stability a central issue for applied ecology, the study of the environment and anthropogenic alterations within it.

A typical form of instability may occur due to anthropogenic management of a natural process with a specific (most often economic) goal in mind and according to a specific design. We have called this kind of instability "conductive instability" (9). As a rule, these phenomena occur due to incomplete knowledge of ecological patterns which leads to the unsuccessful implementation of a system for managing natural processes. Pest control using insecticides serves as a salient example of the aforementioned situation. This paper will focus on this problem.

With current levels at five million tons per year, world pesticide production continues to grow (15). Circulating in the environment, these substances are known to disperse over great distances, and they are not easily decomposed. They considerably perturb biotic elements of natural ecosystems and in some instances human health. At the same time, insecticide production and use in forestry and agriculture continue to increase. In 1950 pesticide production in the USSR totaled 5,100 tons (active mass); in 1980 this figure stood at 283,000 tons (8). Annual pesticide production in the United States rose from 90,000 to 900,000 tons between 1946 and 1976 (9). Pesticide production is not only expanding in terms of volume but is also becoming increasingly diversified. This diversity peaked in 1967 with some 30 new compounds (22). This figure dropped to ten by 1975.

Costs for pesticide production have also risen. If we consider DDT costs as 100 percent, toxaphene is 109 percent, methylparathion is 209 percent, malathion is 359 percent, and carbaryl is 364 percent. Since pests develop resistance to insecticides, new compounds are being developed and used. For example, insecticides sprayed on cotton crops in the United States were introduced in the following order: DDT - toxaphenemalathion - methylparathion - monocrotofos - carbaryl - chlordimeform - synthetic peretoroides (15).

Despite vigorous quantitative increases, qualitative improvements, and financial investments of billions of dollars in pesticide production and use, the damage from pests and arthropoda has not diminished. In some cases it is even rising. This seemingly paradoxical situation calls for an in-depth, quantitative analysis, applying up-to-date ecological concepts and mathematical simulation of ecological processes. Such an effect cannot be explained from the standpoint of conventional ecological wisdom.

This problem can be broken down into the following basic stages, incorporating the methodology proposed earlier for analyzing and addressing such situations (5,11):

- Inventory and analysis of the existing operational strategies for chemical control of pests (including mites) in forestry and agriculture;
- Examination of how insecticides are diffused and transformed in the environment and of their circulation in natural geophysical media;
- Systematic investigation of the sensitivity of pest and mite

groups to currently used and potential insecticides and comparison with assesments of the sensitivity of useful entomofauna (including those which regulate arthropoda abundance) to these insecticides.

- Construction of mathematical models of spatially distributed "plant - phytophagan - entomophagan" systems to simulate dynamic processes resulting from pest control programs, particularly from insecticide use, to assess ecological and economic effects, and to develop well-documented recommendations on how to implement the aforementioned measures.

We shall touch upon only several of the aspects related to the range of research conducted both in the USSR and abroad.

Insecticides are currently applied primarily via aircraft spraying in the form of small and very small droplets. A portion of a sprayed insecticide evaporates; another fraction is transported as aerosol from the treated area. The average diameter of the small droplets is 20–250 um; the diameter of very small droplets is 5–120 um. Some chemicals do not reach the target area and are deposited onto plants and soil. Losses of this nature are at times as high as 97.5 percent depending on weather conditions, the area of the treated territory, flight altitude, sprayer and insecticide parameters, and other factors (3).

In formulating decisions on pest control strategies, these peculiarities must be considered. However, we must disregard these differences in the theoretical analysis of a given situation in order to generate integral characteristics of how a compound behaves in the environment after it is used.

We infer the following concepts to obtain approximate, *a priori* assessments. The maximum concentration C_{io} of a compound in an i-th component of the ecosystem on a treated territory is assumed to be proportional to the amount applied P, $/P/ =$ kg/ha:

$$C_{io} = a_i P,$$

where a_i is the proportionality coefficient. The concentration C_i changes exponentially with time:

$$C_i(t) = C_{io} 1^{-t/Ti}$$

where t is the time period from the moment the compound is applied, and Ti is its lifetime in an i-th component of the ecosystem.

Table 1

Estimates of coefficient a_i

Ecosystem Components	Measurement Units	Value a_i	Data Source
Leaves	ug/cm^2	1.7 ug/cm^2 ha/kg	18
Flowers	mg/g	1,133.0 ug/g ha/kg	7
	mg/g	29.0 mg/kg ha/kg	7
Phytophagan	mg/g	3.4 mg/kg ha/kg	12
Water	ug/l	40.0 ug/l ha/kg	17
Litter	ppm	22.0 ppm ha/kg	25
Air	mg/m^3	1.0 mg/m^3 ha/kg	3
Soil	mg/kg	1.3 mg/kg ha/kg	13

where t is the time period from the moment the compound is applied, and Ti is its lifetime in an i-th component of the ecosystem. We have made approximate evaluations of the model parameters using published data (Tables 1 and 2).

Plants take up dimethoate, a systemic insecticide, from soil; therefore, its concentration in plants is an order of magnitude higher than in soil (12). Since this process is more relevant to health and sanitation issues, it will not be discussed here.

We shall examine the transport of insecticides from treated parcels, using data cited in studies (3) and (19). The amount of insecticide outflow is dependent upon its physical and chemical characteristics and the area of the treated parcel. On average it is estimated to be 50 percent. Mathematical expectation of the deposition mass changes exponentially, the index of change being $0.00023\ m^{-1}$. Aerosol clouds can induce high local mortality rates at distances of up to 20 miles (32 kilometers) and probably even further (21).

Studies (1) and (8) discuss the process of aerosol distribution. Particle size distribution over the surface of plants and soils and in the air at varying distances from a release point has been determined from the turbulent diffusion equation using the Monte

Table 2

Insecticide lifetime in ecosystem components in days

Ecosystem Components	Compounds	
	Dimethoate	Carbaryl
Canopy leaves	6	5
Undergrowth leaves	7	-
Grass	4	-
Litter	6	-
Soil	8*	12
Water	-	4
Internal Plant Tissue	3	-
Nectar	14	-

* Ground-level spraying of dimethoate onto litter = 3 days; subsoil application = 13 days (23)

Sources : (4),(16),(19),(23),(24)

Carlo method. One-um particles are shown to travel considerable distances. The authors note significant air pollution due to use of very small droplets.

Distribution of sprayed insecticide particles should be determined not only spatially but also in terms of their directly reaching the "target." This is particularly true regarding pest worms. Current continuous sprayers with 50 um droplet size are used against pests; such droplets were detected on 93 percent of the insects killed. The "dry aerosol" technique currently under development would reduce droplet size distribution and enhance (theoretically at this point) insecticide effectiveness (20).

Droplet size distribution is usually log-normal. For example, droplet diameter greater than 30 um accounts for 0.5 percent of the total number of droplets in an aerosol cloud one kilometer away from the aerosol source. The 5–30 um size range totals 16.5 percent, and those droplets less than 5 um—33 percent. Droplet

Table 3

Insecticide droplet diameter in the plume and various targets

Particle Diameter (um)	Size Distribution in the plume	on glass receptors	on worms	on needles
6	94.54	15.2	10.7	60.8
6-10	3.92	6.5	50.7	25.8
11-15	0.14	9.6	25.3	9.3
16-20	0.28	13.5	8.7	2.6
21-25	0.14	6.8	3.3	0.5
25	0.7	48.4	1.3	1.0

Source: (20)

diameter exceeding 30 um accounts for 10 percent of insecticide volume: the 5–30 um size is 80 percent, and the under-five um size totals 10 percent (10). Table 3 shows the dispersal breakdown for compound droplets and particles deposited on various targets.

The physiological effects of all or most of the toxic chemicals under consideration should target the nervous system components of arthropoda. For example, carbaryl and dimethoate are known to affect acetylcholinesterase. The latter regulates the amount of cetylcholine, the ubiquitous mediator of the *Animelia* nervous system. We shall not go into detail here on these physiological and biochemical points.

The existing pathways by which insecticides enter insect organisms include contact with leaves and needles, perorale, through the trachea system, and via direct deposition from the atmosphere onto the insect. We can determine the respective fluxes from data on food consumption and respiration rates generated by laboratory experiments to examine pest physiological and biochemical characteristics; their sensitivity to insecticides; insecticide properties; and distribution parameters in the environment. Separate evaluations should be made for phytophagan and entomophagan

Table 4

Direct insecticide deposition onto insects (ug min $^{-1}$g^{-1})

Pest Group	Ultrasmall Spraying Capacity		Small Spraying Capacity	
	Carbaryl	Dimethoate	Carbaryl	Dimethoate
Immobile (phytophagan)	70	52	10	7.5
Mobile (entomophagan)	7000	5200	150	112

insects since they differ in terms of mobility and exposure rates and are at different levels in the trophic chain.

Tentative assessments made for a number of toxic chemicals (carbaryl and dimethoate are included for their low volatility) demonstrate that the amounts of these chemicals which enter insect organisms through their trachea system are negligible compared to other pathways. We shall, therefore, discuss in depth insecticide deposition onto insect bodies. Deposition is closely associated with the speed of air motion near the object, or the speed of the object's movement in a stable air mass.

It should be noted that compound deposition rates increase with wind. At a wind speed of 3 m/s, 8 um diameter droplet deposition increases 100-fold; 57 um increases 15-fold (2). Drawing from these data, we can determine deposition rates on pests (phytophaga and entomophaga) over those fields treated by chemical methods of pest control. Assuming that 57 um droplets and 8 um droplets are primarily present in the air under generally accepted standards for insecticide use, compound fluxes onto insects over a treated parcel is described in Table 4.

Our estimates indicate that within the physiological target area—the acetylcholinesterase molecule—insecticide fluxes generated over fields undergoing pest control measures are appreciably greater than the LD_{50} flux (3.2×10^{-6}ug $g^{-1}min^{-1}$ for carbaryl, and 3.7×10^{-1}ug $g^{-1}min^{-1}$ for dimethoate). The amount of pesticide used is determined based on plant protection practices.

However, the effect of an insecticide which has been sprayed is not limited to the area of its application alone. The indicated deposition rates refer to the area subjected to pest control. An air mass containing insecticides moves in space, although turbulent diffusion and deposition gradually reduce its insecticide concentrations. The area of highest fast-flying pest mortality is considerably greater than the chemically treated area. Furthermore, fast-flying pests in turn "diffuse" inside the air masses containing insecticides. Preliminary calculations indicate that the damage to mobile entomophaga from small droplet spraying is at least an order of magnitude higher than the damage to phytophagan insects.

CONCLUSIONS

Harmful arthropoda and mites cause considerable damage to agricultural systems and woodlands, the most valuable resources available to man. "Reprisal measures" which are used such as extermination programs usually involve no more than the use of toxic chemicals affecting phytophagan insects, excluding methods of biological control. Chemical pest control generally proves cost effective for those areas where the toxic chemicals are directly applied. The value of the biomass which is saved exceeds outlays for extermination measures.

However, in using this one-sided, non-ecological criterion to judge chemical control effectiveness, ecologists and plant protection specialists overlook adverse, non-local, ecological consequences of pesticide use. Uncertainties as to the effectiveness of chemical control from the standpoint of global criteria are underscored by the relatively constant, large areas of crops which continue to be destroyed by pests. This is true despite increased chemical production, technological improvements in their use, and heightened toxicity.

It is our view that the nature of insecticide behavior in the environment—the mechanisms by which they deposit on insects, their long-range distribution, and the relative toxic effects on phytophagans and entomophagans (which are affected at distances far exceeding areas directly treated with compounds)—triggers a gradual spatial destabilization of the "plant - phytophagan - entomophagan" trophic chain, not to mention other adverse effects from insecticide-induced contamination of the environment. In addition, man must increasingly bear the cost of phytophagan insect mortality, induced "free of charge" by their natural enemies, entomophagan insects.

These factors point to the benefits of developing a new approach for assessing the effectiveness of toxic chemical use in forestry and agriculture based on global criteria. To achieve this requires synthesizing knowledge on geophysical behavior patterns of compounds in the environment (including long-range transport) and ecotoxicological data on biota sensitivity to current and future uses of chemicals. It also calls for quantitative analysis of the synecological effects of various forms of chemical pest control.

In view of the global nature of the problem and the convergence of the practical tasks involved in formulating concrete decisions regarding the use of toxic substances in forestry and agriculture, it becomes both desirable and practical to pool the efforts of research teams from various countries. This would facilitate confronting the aforementioned problems of theoretical and applied ecology within the framework of both bilateral and multilateral international projects.

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Problems of Monitoring Stratospheric and Tropospheric Ozone

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Investigations of atmospheric ozone have broadly and rapidly expanded in recent decades due to the detection of potentially significant anthropogenic impacts of diverse scales on ozone levels in various parts of the atmosphere (1,3,9). Scientists have used primarily mathematical models of radiation, photochemical, and other atmospheric processes to study the potential weakening of the atmosphere's "ozone shield." Such a trend would consequently perturb various components of the biosphere due to increased fluxes of ultraviolet solar radiation. In addition, these models involve a large number of laboratory and *in situ* measurements from various platforms (including space-based), incorporating state-of-the-art measurement technology.

From the broad range of issues concerning this extensive subject, this paper will briefly overview findings from an analysis of global distributions of total ozone levels (TOL) and its vertical distribution (VOD) in northern hemisphere air masses. It will then discuss model assessments of the effect on TOL and VOD of various impacts from atmospheric gas and aerosol constituents that originate primarily from human activity. This paper will also consider these factors in terms of the potential evolution of man's activity in the future.

VOD AND TOL IN AIR MASS INTERFACES OF THE NORTHERN HEMISPHERE

Analysis of the highly variable distributions of VOD and TOL in the stratospheric and tropospheric ozonosphere indicates that they are most uniform within the boundaries of three primary air masses: tropical, temperate, and polar (7,8). We detected sharp fluctuations at their boundaries corresponding to subtropical and subpolar global fronts, with lines of maximum wind velocity at isobar surfaces of AT_{200} and AT_{300}, respectively. With sharp daily variations in boundary locations, the median monthly latitudes and altitudes undergo fluid seasonal variation yet little interannual movement. VOD and TOL are also consistent within the area occupied by these three primary air masses. Due to the great homogeneity of VOD and TOL distribution and temperature at the interfaces of the three aforementioned air masses, their median quarterly deviations (MQD)—δ_x, δ_o, and δ_t—from their mean mass area values are significantly less than the deviation (MQD) of these elements from the median values for the zonal belts, which are similar in terms of area of air mass. These belts are usually used in climatological analyses and forecasting.

Figure 1 illustrates this clearly. It presents fluctuations of median annual TOL for 1979-1984, and mean values for the air masses under study and for the zonal belts from (9). This considerably reduced variability of meteorological field "noise" significantly eases and clarifies the task of determining small-scale trends in climatic elements (3). The weak trend towards two percent TOL reduction in the Arctic mass for 1975-1984 is easily discerned from Figure 1. This trend is not visible for mean TOL in the 60°–75° north latitude zone. With values two- to three-fold greater, it also precipitously diminishes the statistical reliability of determinations of median value trends.

Minimal mean TOL for 1983 ($\bar{X}_9$) is clearly seen in Figure 1. It is associated with the global impact on TOL and VOD of aerosol and gas products of the El Chichon eruption. The greatest reduction ($\Delta\bar{X}_9/\bar{X}_9$) reaches four percent of the average for the approximately thirty-year period of mass land-based TOL measurements. It occurs in moderate and Arctic air masses where interannual variability of $\bar{X}_9$ does not exceed 32 percent of the average.

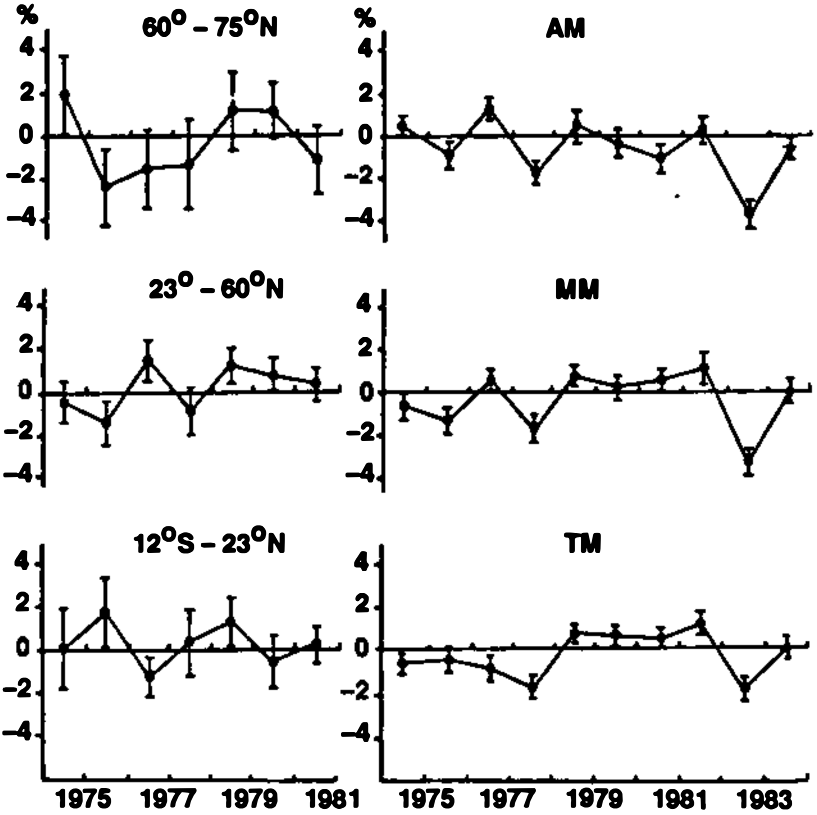

FIGURE 1 Mean annual TOL deviation from the average for 1975-1981 with smoothing for sonal belts and air masses.

A distinct ordering of the statistical structure of VOD—dividing it by the air masses indicated above—also allows us to appreciably refine the well-known inverse *Umkehr* method for determining VOD by land-based measurements with varying solar zenith angles (3). This procedure mathematically solves the problem for an integral Fredholm type 1 equation. We need the most complete information on the structure of the solution and its possible variations in order to solve this problem with mathematical reliability as well as an error evaluation of an approximated solution using the statistical regularization method. By dividing and averaging VOD for the air masses under study, we can yield such information and significantly articulate the VOD profiles generated by the inverse method (from land-based measurements, using both Dobson spectrophotometers and their analogues, and from the M-83 filter ozonesondes).

Figure 2 presents VOD profiles generated by the aforementioned and "customary" inverse methods, as well as by a chemical ozonesonde. The advantage of the refined inverse method over the customary procedure is obvious (8,10). The refined VOD profiles generated by the method in question with significantly less error are needed to provide references for satellite VOD measurements. They can be used to process the quite abundant temporal measurements yielded by the inverse method. We can also articulate VOD fluctuations over time. This is an important area for study in ozonosphere climatology.

OZONE IN THE TROPOSPHERE

With the availability of an ever increasing volume of measurements and model investigations of troposphere photochemistry under background conditions of the earth's atmosphere and in the polluted lower atmosphere over major urban and industrial areas, we have been able to ascertain the climatology and cycles of tropospheric ozone (TO). These factors are, to a large extent, independent of stratospheric ozone (3,12).

In addition to toxic impact (TI), TO sets off a radiation and greenhouse effect. It makes a considerable contribution to ultraviolet (UV) solar radiation absorption, including biologically active uptake (4,6). Our measurements indicate that significant TO variability is associated with its photochemistry and transport. This variability is comparable to the clearly established high variability of TOL which is determined by fluctuations in ozone levels in the layer of its maximum density in the lower stratosphere (below 25 kilometers). Such fluctuations are primarily dependent upon air mass transport. Study (4) has shown that a 2.4-fold increase in tropospheric ozone levels is sufficient to compensate for the upturn in eritic UV radiation in average conditions induced by reduced ozone concentrations in the middle and upper stratosphere layers. There it is broken down by chlorofluorocarbon and hydrocarbon compounds.

TO research, together with the entire range of photochemistry of the "pristine" and polluted troposphere, must therefore become an important component of any comprehensive program

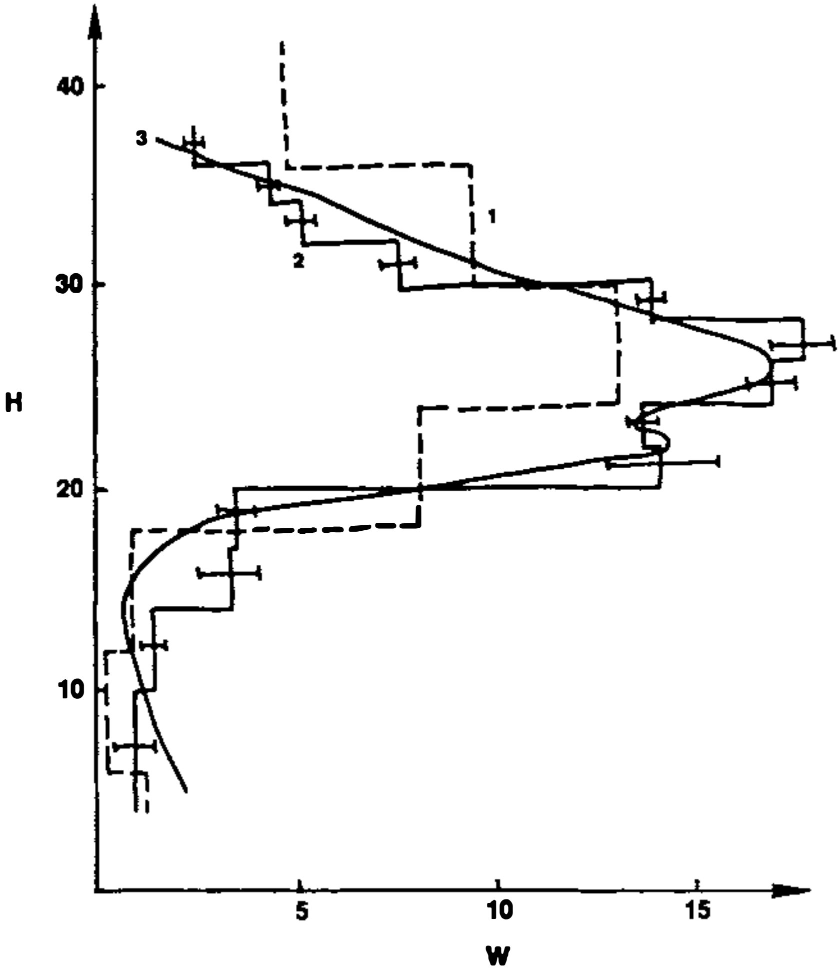

FIGURE 2 Vertical profiles for ozone concentrations (Dobson units per kilometer) January 4, 1985, over Hilo (Hawaiian Islands) derived from (1) the customary reverse method, (2) the refined reverse method, and (3) ozone sensing data.

of stratospheric and tropospheric ozone investigations and monitoring. We should also mention here the great complexity and diversity of photochemical, dynamic, and other factors affecting TO, the closely intertwined system of relationships among these factors, and their high exposure to varying types of anthropogenic impact.

MODEL PREDICTIONS OF STRATOSPHERIC AND TROPOSPHERIC OZONE EVOLUTION

Various measurements made in recent years—including air trapped in gaseous layers of glacier columns—have demonstrated that the median levels of methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and ozone itself in the lower troposphere are growing at a rate as high as one to two percent per year. Methane has been increasing since the 17th and 18th centuries. Increased atmospheric CO_2 levels were detected no later than the mid-19th century. These increases can clearly be ascribed to man's economic activities (5,6,9).

Alterations in the composition of atmospheric trace gases (TG) are directly associated with the atmosphere's photochemistry. They could significantly impact global ozone distribution in the stratosphere and the troposphere. On the other hand, the evolution of atmospheric TG cycles is related to the evolution of the biosphere and impact on it of the growing world economy. Therefore, an analysis of the current status and forecasting of stratospheric and tropospheric ozone evolution must take into account all of these interactions, as well as the nature of present and future fluctuations.

Such analysis and forecasting call for a systemic analysis of the overall "climate"—the atmosphere's constituents of the biosphere—and the world economy as it relates to mankind's current global problems. Several approaches to this kind of analysis and specific, initial results are reviewed in study (4). Study (6) estimates the anticipated growth of global methane and N_2O sources to the end of the 20th century. It uses predictions of world economic development generated by the UN's economic model developed under the direction of Wassily Leontief. These estimates, the findings of other predictive extrapolations of sources and sinks, and levels of these and other trace gases (TGs) can and should be used to study and predict anticipated alterations in stratospheric and tropospheric ozone induced by the entire range of anthropogenic impacts. They should not be limited to any one factor, however significant it might be.

A considerable portion of current model predictions of stratospheric and tropospheric ozone evolution is based on simple, stationary one-dimensional photochemical models (PCMs), with linear extrapolation of current growth trends for discrete factors perturbing stratospheric and tropospheric ozone. An example of this is various CFC concentrations (6,15,19). However, in making predictions the following factors call for the use of multi-dimensional models of the global atmosphere that take into account photochemical, radiation, and dynamical processes and their interactions: localization of primary CFC sources in the mid-northern latitudes and the sizeable growth rates they exhibit with time; the dependency of photochemical reaction rates on temperature and spectral radiation fluxes; and the impact of thermal conditions on dynamics and transport of trace elements.

Such models at their full capacity are not within reach of even the most powerful of today's computers. Knowledge of the physics and chemistry of these processes is also insufficient for constructing complete models. As a result, the most developed predictive evaluations of stratospheric and tropospheric ozone are currently made on the basis of partial sets of one- and two-dimensional radiation and photochemical models. The latter often fail to sufficiently or even slightly account for fluctuations of trace element dynamics and transport induced by the interactions indicated above. Tables of predicted, annual average TG levels in the lower troposphere based on statistics up to the year 2000 and calculated from these models are cited in study (6). Estimates in these tables of anticipated fluctuations in TG concentrations and the limits to their potential fluctuations are in close agreement with similar estimates in other studies (5,6,13,14,15). Estimates of the fluctuations in CFC concentrations generated from two-dimensional, mid-zonal models are substantially closer to what we find in reality than assessments made from one-dimensional models. This is due to the fact that the former account for inter-latitudinal CFC transport from their primary, land-based release points in industrial zones of the mid-northern latitudes.

Figure 3 presents anticipated average annual TOL fluctuations for the extra-tropical northern latitudes to the end of the 20th and into the 21st centuries. These determinations were made by one-dimensional radiation photochemical models (RPMs), with account being taken for temperature variability and its impact on photochemical reaction rates (6,9). The following "scenarios"

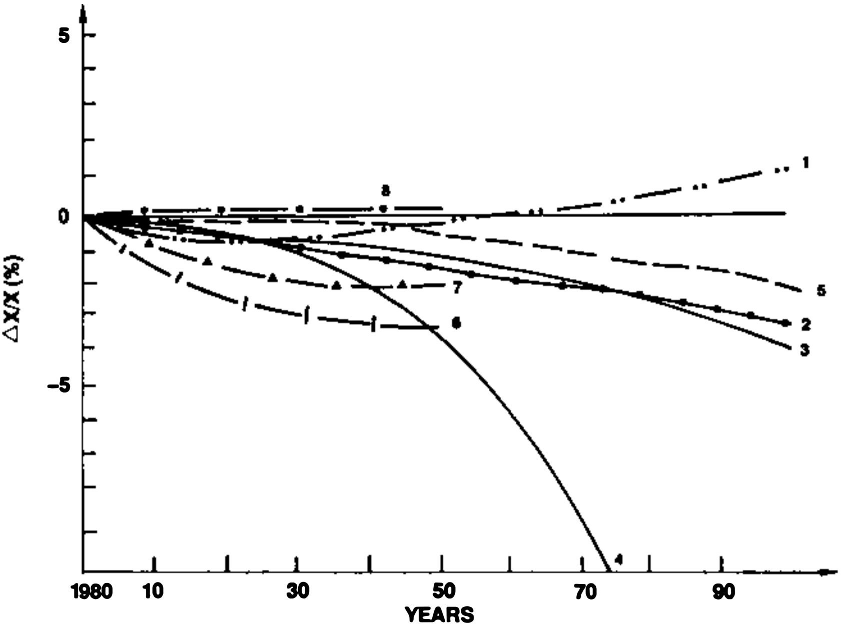

FIGURE 3 Variations with time of the mean annual average TOL for extratropical northern hemisphere latitudes from 1980 levels. Calculations based on estimates from [9] on LLNL RPM for scenario A (1), B (2), C (3), and D (4); on DuPont RPM for scenario C (5); and from estimates on MGO RPM for these same scenarios: maximum (6), mean (7), and minimum (8).

were used for fluctuations in TG discharges into the atmosphere by year (9):

A. Continuous CFC emissions at 1980 levels: 1.5 percent growth in CH_4 emissions and 2.5 percent N_2O emission per year; increase in atmospheric CO_2 levels based on the median scenario in study (15);
B. As in scenario A, but without the increase in CH_4 and N_2O emissions;
C. As in scenario A, but with a 1.5 percent per year growth in CFC emissions;
D. As in scenario A, but with a three percent annual increase in CFC emissions and Main Geophysical Observatory (MGO) RPM estimates, averaging and extrapolating growth extimates for CH_4 and N_2O to the year 2000 (Table 1).

It is clear from Figure 3 that the anticipated reductions in

Table 1

RPM estimates of annual growth
of concentrations and emissions of pollutants

Scenario	Annual growth (%) of near-surface concentrations			Annual growth (%) of emissions into the atmosphere		
	CH_4	CO	N_2O	NO_x[a]	NO_x[b]	CFC
Maximum	2.0	5.0	0.4	5.0	7.0	5.0
Mean	1.5	2.0	0.2	2.0	5.0	0[c]
Minimum	1.0	0	0	0	0	-3.0

a = from land-based sources; b = from air traffic in the upper troposphere;
c = estimated persistence of mean CFC emissions level in 1979-1981.

Source: (9)

TOL for the periods in question will not exceed four percent of initial 1980 levels. An estimate of this reduction as per scenario D for model LLNL in study (9) appears to be greatly overstated. This is due to the deficiencies indicated in study (11). It should be noted that computation of emissions growth for such TGs as CH_4, N_2O, and NO_x and their photochemical impacts with ozone and other TGs in the atmosphere significantly mitigates the drop in TOL and the increase in CO_2, resulting in an enhanced greenhouse effect: warming in the troposphere and cooling in the stratosphere.

This important factor is clearly delineated in Figure 4, constructed from the findings cited in study (9). It presents calculations from a one-dimensional RPM of fluctuations in the mean annual and average VOD for the extratropical northern latitudes. This is induced by fluctuations in ambient TG and CO_2 levels as shown in Figure 4. It is clear from this figure that TOL reduction with a CFC increase was induced by a precipitous (nearly double) decrease in (O_3) in the middle and upper stratosphere. This decrease drops, however, by nearly one-half, primarily due to stratospheric cooling from the doubling of current atmospheric CO_2 levels. TO increase with a doubling of atmospheric CH_2 and

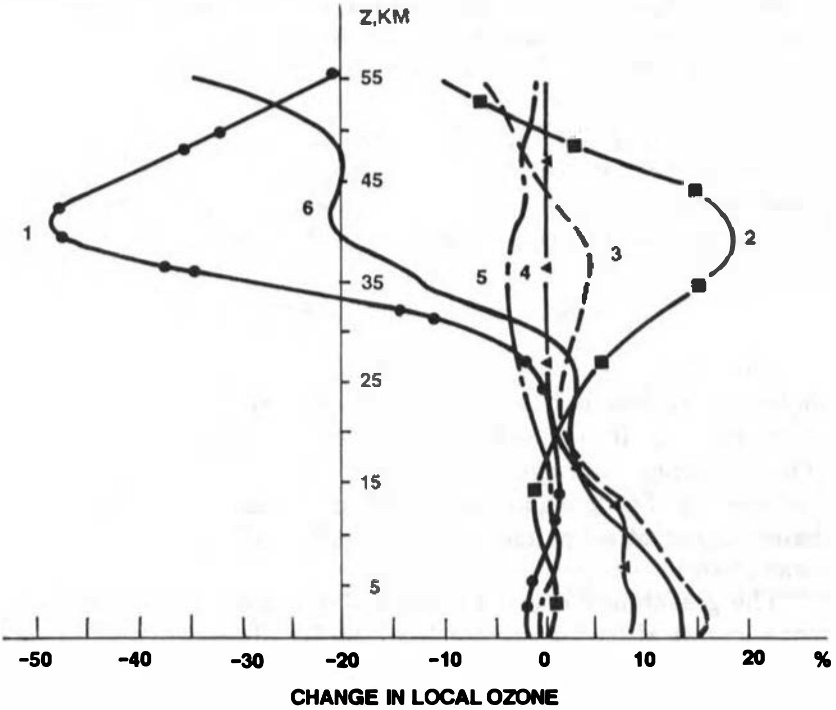

FIGURE 4 Variations in the mean annual average VOD for extratropical northern latitudes from estimates on LLML RPM for: (1) increasing levels of Cl_y to 8 billion^{-1} by volume in the stratosphere; (2) doubling CO_2 in the atmosphere; (3) doubling CH_4; (4) doubling CO; (5) increasing N_2O by 20 percent; and (6) total effect without including CO increase.[9]

CO partially compensates for the (O_3) downturn in the stratosphere. The total diminished level of TOL is formed as a difference of approximately 20 percent of (O_3) reduction above 30 kilometers and of the same increase in (O_3) in the troposphere.

EFFECTS OF INVERSE RELATIONSHIPS

In this way, inverse relationships between temperature variations and photochemical reaction rates—and between variations of a variety of TG concentrations and ozone—essentially lead to a reduction in the aggregate effect on ozone as compared to the effect of a unique perturbing factor which does not account for these relationships. Stratospheric cooling induced by increased CO_2

concentrations and, to a lesser degree, by increased atmospheric CH_4, N_2O, and CFC diminishes the destruction rate of ozone, Cl, ClO, and NO_x due to the temperature associated reduction of rates for the corresponding gaseous phase reactions. The effect of the rapid jump in CFC release into the atmosphere—freon-12, to be more precise—serves to substantially offset the impact of increased CH_4. The latter converts a portion of atmospheric C in the stratosphere into non-active HCl in the reaction:

$$Cl + CH_4 \rightarrow CH_3 + HCl \qquad (1,6)$$

The upturn in CO discharges and particularly of NO_x from land-based release points into the troposphere enhances intensive TO formation. It is therefore impossible to predict man-induced TOL variations (and even more so for VOD) purely on the basis of inferences of potential future CFC emissions. We need to assess the evolution of all primary TG and CO_2 concentrations in the atmosphere.

The greenhouse effect, substantially enhanced by anticipated ozone loss at altitudes greater than 25–30 kilometers and by TO increase, will induce a noticeable restructuring of atmospheric circulation. We believe that an enhanced vertical exchange in the stratosphere and through the tropopause is a strong possibility due to weakening of static stability in these layers of the atmosphere (1,6). Intensified mean vertical transport in these layers will clearly exert a considerable impact on VOD and on the entire range of atmospheric chemistry. However, this intensification is scarcely accounted for in current, even one-dimensional BRPM. At the present stage we are not exactly certain how to accomplish this. It is unclear just how suitable large, detailed, three-dimensional models of planetary atmospheric circulation are for this purpose. The minor yet long-term effect of enhanced vertical transport is difficult to detect in these models against the background of much more intensive dynamical transport variations.

Our assessments of anticipated VOD and TOL variations under potential anthropogenic impact invite further discussion in view of the points discussed above. Our general conclusion regarding the estimate of probable TOL fluctuations does not exceed the accuracy of existing RPM versions. Long-range TOL trends cannot be reliably detected with great certainty. However, VOD variations may be substantial: increased TO concentrations and depleted ozone above 25–30 kilometers could enhance the greenhouse effect and influence the planet's atmospheric dynamics below 50 kilometers.

ACKNOWLEDGEMENT

We wish to cite the assistance of V. Komkhir, G. Peterson, and other colleagues from NOAA's Geophysical Climate Change Monitoring Program in providing data on concomitant ozone sensing and inverse method measurements at various sites in the United States.

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Stratospheric Ozone Depletion and Its Effects

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By preventing most potentially harmful ultraviolet radiation (UV-B) from penetrating to the earth's surface, the ozone layer acts as a shield protecting human health, welfare, and the environment. Ozone is continually created and destroyed in a natural cycle discovered by Chapman in the 1930s. Oxygen (O_2) is dissociated by short wavelength ultraviolet radiation into singlet oxygen atoms (O), which then combine with O_2 to form ozone (O_3). In turn, ozone is transformed into O_2 and O. This natural cycle of ozone creation and loss determines ozone abundance. The cycle can be influenced by many chemical species and other factors. As a result, ozone varies latitudinally, seasonally, and annually around long-term means.

The possibility that anthropogenic forces could upset this cycle was raised in the early 1970s. Scientists feared that the space shuttle and large numbers of supersonic transports would inject exhaust emissions containing nitrogen and chlorine into the stratosphere and would interfere with the mechanism described by Chapman. Acting as a catalyst, each nitrogen or chlorine atom would react with thousands of ozone atoms. Because the destruction rate of ozone would be increased, its equilibrium abundance would be decreased.

The possibility that chlorofluorocarbons (CFCs) could cause the depletion of stratospheric ozone was first theorized in a 1974 article in *Nature* by Molina and Rowland. They pointed to two CFCs in particular, CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2). Concentrations of these compounds—which were being used increasingly due to their stability, low thermal conductivity, and non-toxicity—had been found to be nearly uniform throughout the global atmosphere. This finding prompted Molina and Rowland to explore loss mechanisms for these CFCs. If they survived long enough to become uniformly dispersed in the air, what was their eventual fate? Molina and Rowland theorized that the CFCs would survive until they were eventually transported to the stratosphere. Photo-dissociation of the CFCs would produce significant amounts of chlorine atoms which would be free to enter into catalytic cycles that destroy stratospheric ozone. Despite the many scientific uncertainties which complicate our understanding of this mechanism, twelve years of intensive research have reinforced the basic outline of this CFC/ozone theory.

If the ozone level were to decrease, more UV-B, especially that of the most damaging wavelengths, would penetrate to the earth's surface. The health and environmental effects of this increased exposure could be profound. Scientists believe that the creation of the ozone layer was a necessary condition for the evolution of life on earth. While organisms exist with current UV-B levels, increased UV-B levels would undoubtedly cause harm to individual organisms and alter existing relationships between organisms. For humans, disruptions from UV-B could increase skin cancer (including melanoma), suppress the immune system, and damage the eye. Aquatic and terrestial ecosystems would be perturbed. In addition, increases in UV-B would accelerate the natural "weathering" of outdoor materials and increase tropospheric oxidants.

ATMOSPHERIC RESPONSE

The likelihood of these dangers will be influenced by the future concentrations of trace gases, such as chloroflurocarbons (CFC-11, -12, -113, and -22; and Halon-1211), Halon-1301 (not a chlorofluorocarbon), chlorocarbons (CCl_4 and CH_3CCl_3), and other gases that counter ozone depletion (CO_2, CH_4, and under some high-chlorine cases, N_2O). Current atmospheric measurements show that concentrations of CFCs are increasing and that the increases have generally been consistent with past growth in emissions. Historically, CFC use has closely coincided with economic growth in the United States, growing about twice as fast as GNP. CFC-113,

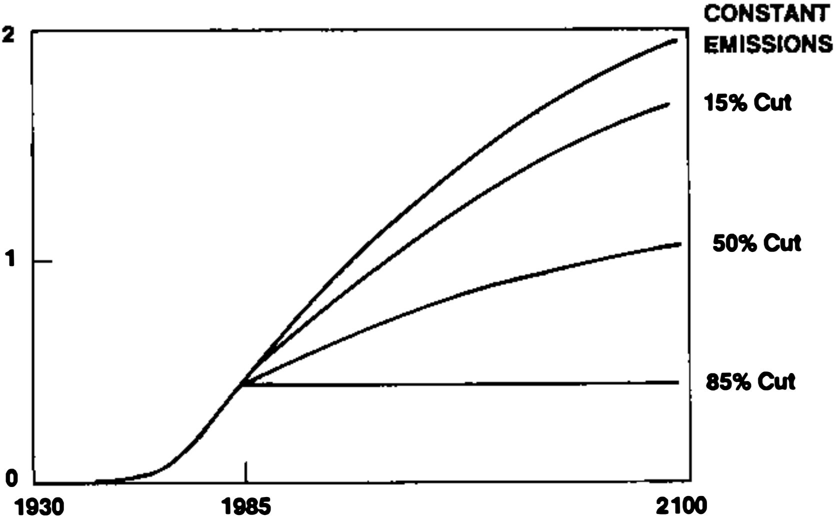


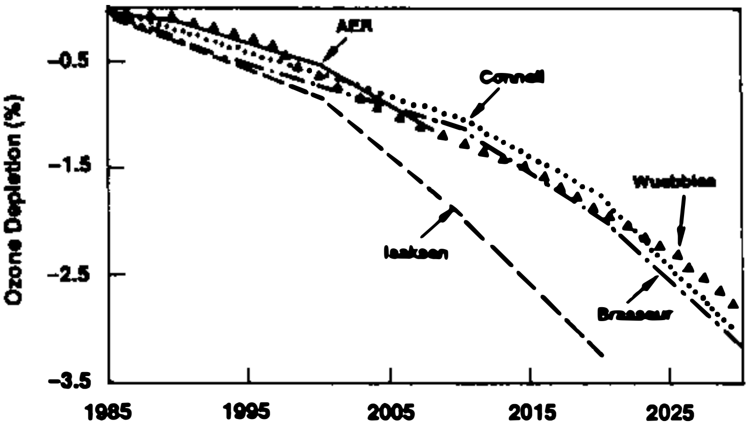
FIGURE 1 CFC-12: Atmospheric concentrations from different emission trajectories (ppbv).

which is used by the electronics industry, has grown even faster. Halon-1211 concentrations are growing at 23 percent per year.

Extensive economic analysis conducted by several authors for a variety of geographic areas shows that such long-term growth will continue and concentrations of CFCs will increase. Due to the long atmospheric lifetimes of CFCs, it should be noted that concentrations would continue to increase even if emissions were held constant (Figure 1).

To explore the changes in ozone due to concentrations of CFCs and other trace gases, measurements of recent changes in ozone levels and measurements of trace gases should be compared to estimates of models developed to project ozone abundance. Consistent with model predictions, a range of monitoring techniques using balloons, satellites, and ground-based instruments show small but significant decreases in ozone of approximately three percent in the upper atmosphere at mid-latitudes and an increase of 12 percent (from a smaller base) in the lower troposphere. Also consistent with model predictions, it appears that no significant net change in total column ozone occurred for the period 1970–1980.

Models can be compared with current atmospheric observations. These comparisons show that current models provide a



Global average change in total column ozone as calculated by several modeling groups for a common scenario of:

Compound	Growth Rate (% per year)
CFCs	3.0 (emissions)
CH_4	1.0 (concentrations)
N_2O	0.25 (concentrations)
CO_2	-0.60 (concentrations)

Results shown for 2-D models of Isaksen and AER, 1-D models of Brasseur and Wuebbles, and Connell's parameterization of the LLNL 1-D model.

FIGURE 2 Model comparison for coupled perturbation scenario.

relatively good replication of most observations but produce some inconsistent results. For example, differences in ozone levels at 40 kilometers reduce overall confidence in model reliability. The failure of models to predict or explain the behavior of the Antarctic ozone hole constitutes another modeling problem for which the implications are still unclear.

Relatively good agreement can exist among different models. For example, one-dimensional models that treat the world as a single column of air and two-dimensional models that incorporate seasonality and latitude provide roughly similar results (Figure 2). Of the two model types, two-dimensional models project higher average depletion and show more depletion at greater distances from the equator (Figure 3).

Different one-dimensional and two-dimensional model projections of future ozone levels depend significantly on the precise

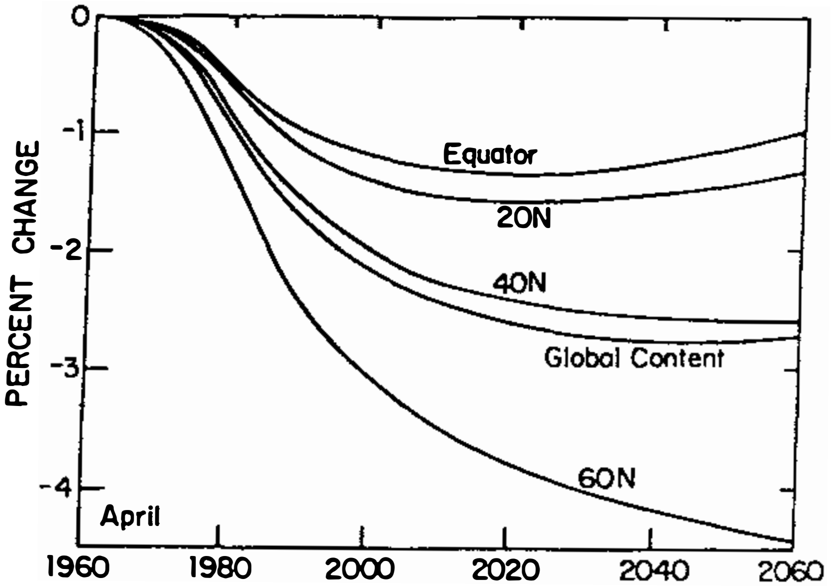


FIGURE 3 Calculated percent changes in the column abundance of O_3 for April at selected latitudes for the years 1960 to 2060 for Scenario A (no CFC growth).

scenarios of trace gas emissions and the choices of boundary conditions. However, the one robust finding that emerges from an extensive number of model runs is that if CFC emissions grow even slightly, ozone depletion will occur even if greenhouse gases that counter ozone depletion also continue to grow.

RISKS TO HUMAN HEALTH

The major consequence of ozone depletion would be an increase in UV-B radiation at ground level. Because of changes in the solar angle and a natural gradient in the ozone layer, the latitudinal exposure to UV-B varies greatly with more UV-B received by those organisms living near the equator. Extensive epidemiological studies that relate this natural variation in UV-B to skin cancer incidence and laboratory studies that measure the effect of artificial UV-B on animals conclusively demonstrate that the two most common types of skin cancer—basal and squamous—are both associated with cumulative exposure to UV-B. There are approximately 500,000 cases of the disease per year in the United States although less than one percent of these are fatal. A relatively good understanding of these cancers now exists, with a one percent ozone depletion increasing basal skin cancer by one to three percent and squamous skin cancer by two to five percent.

Melanoma is a less common though far more dangerous type of skin cancer. Recent studies of melanoma seem to reinforce the hypothesis that UV-B is one of its causes although the relationship appears much more complex and is perhaps related to peak exposures and possibly to exposures during youth.

Laboratory experiments and case studies demonstrate that UV-B can suppress the immune systems of animals and humans. This suppression is thought to be a factor in the development of skin cancer. Two infectious diseases—herpes and leishmaniasis—also appear to be affected by UV-B although other diseases have not been studied. In addition, although scientific understanding of the causes of cataracts is incomplete, UV-B exposure appears to be one factor contributing to their development. Epidemiological, animal, and biochemical studies provide support for this hypothesis.

RISKS TO AQUATIC AND TERRESTRIAL ECOSYSTEMS

There are difficulties in designing experiments which attempt to investigate the effects of UV-B on ecosystems. While few crops have been studied in detail, 23 cultivars of soybean have been examined; two-thirds of these were found to be sensitive to UV-B radiation. Long-term field studies of one sensitive cultivar show that a 20 percent depletion of ozone could produce a 25 percent reduction in yield. At this time, it is unknown how other cultivars would respond to higher UV-B. However, experts at a recent meeting of the UNEP Coordinating Committee on the Ozone Layer concluded that based on limited field and laboratory experiments, "increases in UV-B radiation would reduce yield in crops and alter composition among plants." Laboratory experiments have shown that lower aquatic forms such as phytoplankton and zooplankton have low tolerances to UV-B. Enhanced UV-B exposure might alter the community composition of these organisms. Increases in UV-B have also been shown to decrease the survival rates of larvae. The combined effects of these perturbations is unknown because of two confounding factors. First, exact estimates of exposure are complicated by ocean turbulence and natural mixing of organisms. Second, uncertainties regarding the lifecycle of organisms in natural ecosystems make the relative importance of changes in survival rates and community composition difficult to gauge. Thus, while the risk to aquatic species has been demonstrated by experimental studies in laboratories, our inability to experiment under natural conditions has limited our ability to quantify the dimensions of these possible effects.

OTHER TYPES OF RISKS

UV-B radiation harms polymers, including many materials used outdoors such as pipes and siding. The resulting cracking, yellowing, and weakening can be controlled by adding UV stabilizers to polymer compounds, but at a cost. Preliminary analysis by Whitten in UNEP/EPA (1986) suggests that increased UV-B would enhance the development of ground level ozone (smog) and hydrogen peroxide, although the implications are still unclear.

ESTIMATES OF FUTURE DEPLETION AND EFFECTS

Using a variety of prior assessments, the US Environmental Protection Agency (EPA) recently performed a time dependent analysis of the possible implications of various rates of growth for ozone depletion and its effects (US EPA 1987). Figure 4 shows

Table 1

Human health effects: central case
(additional cumulative cases and deaths by population cohort)

Health Effect	Population Alive Today (a)	Numbers Born 1985-2029 (b)	Numbers Born 2030-2074 (c)
Non-Melanoma Skin Tumors			
Additional Basal Cases	1,258,900	10,717,600	41,095,900
Additional Squamous Cases	816,100	7,864,600	35,918,100
Additional Deaths	34,500	382,100	1,474,300
Melanoma Skin Tumors			
Additional Cases	13,600	113,400	415,800
Additional Deaths	3,700	29,500	99,200
Senile Cataracts			
Additional Cases	599,900	3,855,500	9,116,300

(a) Analysis period for health effects: 1985-2074

(b) Analysis period for health effects: 1985-2118

(c) Analysis period for health effects: 2030-2164

Source: USEPA, An Assessment of the Risks of Stratospheric Modification (1987)

the depletion levels and assumed scenarios; Table 1 illustrates the effect on skin cancers; and Table 2 shows the other effects. These results should be interpreted carefully as they are subject to wide margins of uncertainty. In particular, many of the effects shown in Table 2 are based on limited case studies which are still in the early stages of research.

There are several major limitations in such analyses. First, they are based on one-dimensional, not two-dimensional, models. Figure 2 shows depletion estimates for the first time-dependent

Table 2

Materials, climate, and other effects: central case

Type of Effect	Effect	Units
<u>Effects Estimated Quanitatively for the United States</u>		
Materials damage (a)	603	Present Value (millions of 1985 dollars)
Rise in equilibrium temperature by 2075 (b)	5.7	Degrees Centigrade
Sea level rise by 2075	98	Centimeters
<u>Effects Based on Case Studies and Research in Early Stages</u>		
Cost of sea level rise in Charleston and Galveston (c)	871 - 2,131	Present Value (millions of 1985 dollars)
Reduction in soybean seed yield (d)	> 19	Percent in year 2075
Increase in ground-based ozone (e)	7.0 - 36.8	Percent in year 2075
Loss of northern anchovy population (f)	>11.0 - >25.0	Percent in year 2075

(a) Discounted over 1985-2075 using a real discount rate of three percent.

(b) Estimated using an assumed climate sensitivity of 3 C (middle NAS estimate). Recent analysis indicates that 4 C may be a preferred central case assumption. Using a 4 C sensitivity, the estimated equilibrium warming in 2075 is about 8.4 C.

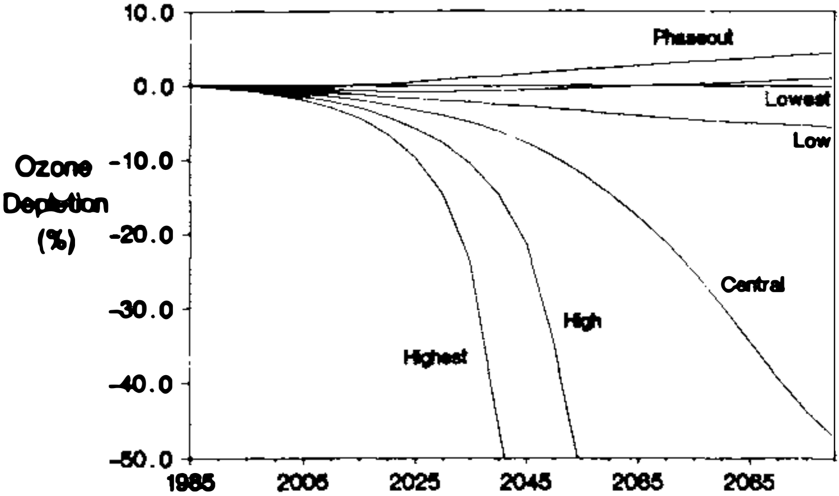
(c) Lowest estimate with anticipation of sea level rise; highest estimate without anticipation.

(d) Essex cultivar only in years of average current climate.

(e) Lowest estimate is for Los Angeles, California; highest estimate is for Nashville, Tennessee.

(f) Lowest estimate assumes 15-meter vertical mixing of the top ocean layer; highest estimate assumes 10-meter vertical mixing.

Source: USEPA, An Assessment of the Risks of Stratospheric Modification (1987)



Reference	Assumptions
Phaseout:	CFC annual use is reduced to zero linearly by 2010.
Lowest:	No growth of global CFC use from 1985 levels.
Low:	Global CFC use grows at a 1.2 percent annual rate until 2050. Use remains constant after 2050.
Central:	Global CFC use grows at a 2.5 percent annual rate until 2050. Use remains constant after 2050.
High:	Global CFC use grows at a 3.8 percent annual rate until 2050. Use remains constant after 2050.
Highest:	Global CFC use grows at a 5.0 percent annual rate until 2050. Use remains constant after 2050.

The following growth rates apply for other trace gas concentrations for each scenario:

Carbon Dioxide (CO_2):	0.6 percent annual growth through 2100 (NAS 50th percentile);
Nitrous Oxide (N_2O):	0.2 percent annual growth through 2100; and
Methane (CH_4):	0.017 ppm annual increase through 2100.

Source: USEPA, An Assessment of the Risks of Stratospheric Modification (1987)

FIGURE 4 Global average ozone depletion: emissions scenarios.

analysis completed with a two-dimensional model and compares the results to the one-dimensional model used in the EPA risk assessment. Clearly, the two-dimensional model shows greater average depletion as well as increased depletion as distance from the equator increases.

Another limitation is the fact that the assessment assumes that CO_2, N_2O, and CH_4 will continue to grow at historical compound rates throughout the next century. However, alternative assumptions are possible. One estimate is that ozone depletion would nearly double if methane, a greenhouse gas, grows even at a much slower rate after the year 2000.

Finally, the most important limitation of current estimates of ozone depletion and its effects stems from incomplete and uncertain knowledge of how the earth will evolve in response to its changing atmospheric composition. Since the processes which govern the earth's atmosphere and natural systems are vastly more complicated than models can describe, accurate prediction of the magnitude and extent of ozone depletion and its effects is difficult. This lack of knowledge is exemplified by the unanticipated emergence of the Antarctic ozone hole, which was so unexpected that scientists from the US National Aeronautics and Space Administration (NASA) initially rejected the early satellite data which identified it, leaving its discovery to the British Antarctic Survey. Several years later, there is still no adequate explanation for the phenomenon.

What is known, however, is that human influence on the global atmosphere is unprecedented in its speed and scope. While the ultimate responses of the earth to these perturbations are impossible to state with absolute certainty, it appears that their ultimate significance will be substantial.

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Integrated Global Background Monitoring Network

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Over geologic time, the biological and geochemical cycles essential for life on earth evolved and established themselves in a harmonious, self-perpetuating equilibrium. However, within the last 100 years and primarily because of industrialization, man's activities have become so significant that they have the potential to adversely influence many of these cycles. For example, total global nitrogen dioxide emissions are currently estimated to be 645×10^6 tons per year, including nitrous oxides emitted by bacterial actions. Industrial sources, including transportation, are estimated at 52×10^6 tons, or eight percent of the total. Similarly, total global sulphur emissions are estimated at 237×10^6 tons per year, with 34 percent coming from anthropogenic sources (Whelpdale and Munn 1976). Patterson (1980) estimates that 99 percent of global lead emissions are anthropogenic in origin. Pacyna (1986) puts the figure closer to 96 percent, still a very large proportion of total lead emissions.

While we cannot at this time accurately assess man's impact on these major global cycles, a number of studies have demonstrated that anthropogenic materials have been transported long distances and deposited in reportedly pristine areas. For example, Elgmork et al. (1973) found that snow in remote areas of Norway contained high levels of sulphur and lead levels of 98 ug/liter and concluded that the pollutants originated in urban and industrial areas of western and central Europe. Johnson et al. (1972) and Schlesinger et al. (1974) reported high acidity, lead, cadmium, and mercury levels in mountainous areas of northern New England in the United States. It was postulated that the pollutants originated in the densely populated, industrial areas of the central and mid-Atlantic regions of the United States. Hirao and Patterson (1974) concluded that 97 percent of the lead found in a remote site in the western United States came from anthropogenic sources. Anas and Wilson (1970) reported DDT levels in the milk and fat of northern fur seal pups. Other studies (Lannefors et al. 1983, Carlson 1981, Rahn 1981) examined potential contamination of the Arctic atmosphere from a variety of mid-hemisphere populated and industralized areas.

A number of studies have been carried out to establish reference levels of compounds with both natural and anthropogenic sources. For example, some researchers have looked at the composition of precipitation from remote areas of the world. Included were such constituents as hydrogen ion concentration, calcium, magnesium, sodium, potassium, ammonia, sulfates, nitrates, chlorides, silicates, and phosphates (Keene et al. 1983, Galloway et al. 1982). Others have looked at atmospheric concentrations over continental and marine areas at varying altitudes for nitrates, sulfates, chlorides, and ammonia (Huebert and Lazrus 1980).

Trace metals also have both natural and anthropogenic sources. Rahn (1976) reviewed the literature up to 1975 concentrating on the composition of atmospheric aerosols with emphasis on remote areas. This effort was updated in 1986 by Wiersma and Davidson.

One of the more significant problems of trying to determine man's impact on global cycles is not knowing what "natural" levels should be for both abiotic processes (e.g., gases and trace elements) and biotic processes (e.g., ecosystem functions). A well-designed, coordinated network of baseline stations in remote areas around the world can provide a data base that will allow current estimates to be made of biotic and abiotic baseline conditions. These baseline conditions will then facilitate better comparisons with more impacted areas and thus contribute to a more complete understanding of man's impact on his world.

This paper examines the history of background pollution monitoring at the international level, describes current activities in the field of "integrated" background monitoring, and proposes criteria for the development of a global network of baseline stations to coordinate background monitoring for the presence, accumulation, and behavior of pollutants in remote ecosystems. In this paper, the network is called the Integrated Global Background Monitoring Network.

The objectives of the Integrated Global Background Monitoring Network are:

- To establish reference levels for pollutants that have both anthropogenic and natural sources;
- To serve as an early warning system for detecting global spread and trends of pollutants that have only anthropogenic sources;
- To establish background levels for selected ecosystem parameters against which data from more impacted areas can be compared;
- To contribute to the study of biogeochemical cycles.

BACKGROUND MONITORING

The general concept for a global baseline monitoring system has been discussed for over 20 years. As early as 1965, a US Presidential Advisory Committee called for worldwide background ecosystem studies (Wenger et al. 1970). Lundholm (1968) recommended the establishment of a global background monitoring system based on a network of remote areas around the world.

Since then, scientists throughout the world have re-emphasized the need for a global monitoring system and for the establishment of a global network of ecological baseline stations (Ecological Research Committee 1970, Ad Hoc Task Force on GNEM 1970). Jenkins (1971) suggested that the stations should be representative of the major ecological biomes of the world and be equipped to measure pollutants. Sokolov (1981) also urged that particular attention be paid to integrated background monitoring, which was defined by a 1980 Expert Group Meeting in Geneva as "the repeated measurement of a range of environmental variables or indicators in the living and non-living compartments of the environment, and the investigation of the transfer of substances or energy from one environmental compartment to another." Izrael (1982) pointed out the early warning value of a global network of background monitoring sites. Rovinsky and Buyanova (1982) observed that such a network of background monitoring sites could provide a basis for international environmental protection.

The World Meteorological Organization (WMO) Executive Committee (now "Executive Council") in its Resolution 17 proposed that:

> (F)or general scientific and economic reasons, members of WMO should ... as far as possible be prepared to meet requirements for environmental monitoring in other media (than air) as formulated by national or international organisations ... (M)onitoring in soil and biota should also be accepted to be carried out at background air pollution stations as far as feasible.

The idea of a Global Environmental Monitoring System (GEMS) was debated at Stockholm, Sweden, in 1972 at the UN Conference on the Human Environment, and a GEMS Program Activity Center was established in 1974 within the Nairobi, Kenya, headquarters of the United Nations Environment Program (UNEP).

An interagency working group (Task Force II: Committee on International Environmental Affairs 1976) was convened in 1974 to determine what should be monitored and to make recommendations for the structure and operation of an environmental assessment service within UNEP. The working group proposed an "Earthwatch" component within UNEP which would have four integral parts: monitoring (GEMS), research, evaluation, and information exchange. The working group also established the principle that environmental assessment should be carried out, wherever possible, in cooperation with similar activities, either existing or planned.

In addition, the International Environmental Programs Committee (1976) of the US National Research Council suggested linking MAB's Biosphere Reserve Program to terrestrial monitoring within GEMS. Franklin (1977) also argued that biosphere reserves be considered a component of GEMS. Herman et al. (1978) and Wiersma et al. (1978) described potential monitoring activities in US biosphere reserves. Finally, the International Coordinating Council of the Program on Man and Biosphere (MAB) (Anon. 1978) officially recognized the link between GEMS and MAB's Biosphere Reserve Program.

Currently, only WMO has a worldwide background air pollution monitoring network which is known as BAPMoN (Kohler 1980). However, only about 10 percent of the more than 100 BAPMoN sites are truly "baseline" (de Koning and Kohler 1978). The terminology is slightly confusing: WMO uses "background monitoring" to refer to the entire BAPMoN network and "baseline" to designate very remote sites, which in this paper are referred to as "background." In BAPMoN, the term "baseline" is being replaced by "global," indicating the largest representativeness of a monitoring location (> 3,000 km). Other categories of monitoring locations are designated "continental" (> 1,000 kilometers) and "regional" (> 300 km). Several workers (Jensen and Brown 1980, Anon. 1980) have stressed a need for terrestrial background monitoring stations that could provide correlated measures of pollutant behavior in different environmental media (air, water, soils, plants, and animals). Particular attention has been focused on the BAPMoN baseline sites.

The Geophysical Monitoring for Climatic Change (GMCC) program (Mendonca 1979), the Global Precipitation Chemistry Project (Keene et al. 1983), and other similar programs also collect data on atmospheric constituents in remote areas. While more limited in scope than the Integrated Global Background Monitoring Network, the data collected should be valuable and should be considered in the development of the Integrated Background Monitoring Network. Eventually, many of these activities should come under the new International Geosphere Biosphere Program (IGBP).

GEOGRAPHICAL BASIS FOR A PROPOSED INTEGRATED BACKGROUND MONITORING NETWORK

An Integrated Global Background Monitoring Network must have a geographic basis. An ideal candidate for this geographic basis is the existing international Biosphere Reserve System of the MAB Program. There are over 226 biosphere reserves in 62 countries, and over 40 are located in the United States. Obviously, the existing biosphere reserves are far too many for an operational global network. Estimates vary as to the number of sites necessary for representative global coverage. Rovinsky and Buyanova (1982) estimated that 30 to 40 sites would be needed. Jenkins (1971) estimated 20, with at least two stations in each of the following biome types: deciduous forest, coniferous forest, tropical forest, savanna, thorn scrub, grassland, desert, and tundra.

Many of the biosphere reserves are not suitable for background monitoring. Wiersma (1981[a]) examined the Biosphere Reserve System in some detail in order to determine which reserves were potentially suitable for background monitoring. The establishment of selection criteria is critical to making an effective choice. The most applicable criteria would seem to be those established for the WMO Background Monitoring Stations as modified in 1979 (WMO 1979). However, a second set of site selection criteria presented by WMO in 1980 appear more directly applicable to the selection of biosphere reserves for background pollutant monitoring. With the removal of reference to specific sites, these criteria formed the basis for the final selection criteria used. The criteria were then divided into two categories: "mandatory" and "desirable." In order to be selected, a site had to meet the mandatory criteria but not necessarily the desirable criteria. Both sets of criteria are described in Table 1.

Actual selection of a subset of reserves based on these criteria is preliminary at this time. Selection was based only on the information available in the Directory of Biosphere Reserves (UNESCO 1979) which covered the 171 biosphere reserves established at that time. The number of biosphere reserves currently in the system has expanded, and the more recent additions should eventually be reviewed for possible use in a background monitoring network. Additional information is also necessary to develop a final list of candidate sites. Examples of the need for additional information beyond that found in the Directory of Biosphere Reserves are:

- Inventories of pollutant emissions and anthropogenic activities within several hundred kilometers of the study area and for a foreseeable future time;
- More information on availability of flora and fauna data;
- More information on past and current research programs;
- Review of existing data bases covering physical data sets (i.e., meteorology, hydrology, soils, etc.);
- More details on the site facilities available;
- Evaluation of reserve position vis-a-vis major air mass trajectories;
- Evaluation of reserve position with regard to major climatic regimes (including types of prevailing air masses);

Table 1

Selection criteria

Mandatory Criteria	Desirable Criteria
1. Size. The size of a reserve can help ensure that several of the WMO integrated monitoring site selection criteria can be met. For example, adequate size will help minimise local influences. It would help ensure that an adequate core area existed and would help shield it against changes in economic activity in surrounding areas. Size chosen was 20,000 ha.	1. Underdeveloped surrounding areas. This would ensure the size and existence of a buffer zone. This criterion, however, was partly met by a mandatory criterion on size; therefore, the criterion was listed as a desirable rather than a required criterion.
2. Access. The area should be reasonably accessible, but intensive activities such as a large number of automobiles, etc., should be restricted.	2. No history of disturbance. While this would ensure a natural ecosystem in the reserve, in practice it would be difficult to find very many reserves which could meet this criterion fully.
3. Protection. The areas should have institutional protection (i.e., state or federal government) in perpetuity. This will not only help protect the area, but in some cases could significantly alter development in the surrounding areas.	3. Permanent staff greater than five. This is based on the premise that the larger the resident staff, the greater is the possibility that the reserve will have suitable facilities and ongoing activities that would be useful to the monitoring program.
4. Staff. The reserve should have a permanent staff. This would increase (but not guarantee) probability that the following services will be available: a) protective oversight; b)scientific studies; c) logistical staging areas; and d) personnel available to carry out routine measurements (e.g., change sample filters).	4. Scientific research underway. Three kinds of research were envisioned: a) pollutant monitoring (abiotic); b) impact studies which could include pollutant monitoring; and c) basic ecology studies.
5. Vegetation. The reserve should have a vegetation type approximately representative of a major biogeographical type in the world.	5. Data availability. The presence of background data for a reserve is not ensured merely because research activities are underway. Examples of essentially required data are: meteorological, geohydrological, geophysical, soils, geohydrological, and biological. The latter would include items such as species lists, forest type, maps, census data, etc.

- Ability and willingness of host country to carry out pollutant monitoring programs;
- Types and quality of graphical support data (e.g., maps, aerial photographs, satellite photographs).

In addition, final selection of integrated global background monitoring sites should not necessarily be limited to biosphere reserves; other sites should be considered as appropriate.

Using the ten selection criteria defined in Table 1, an initial screening of the 171 reserves listed in the Directory of Biosphere Reserves yielded 41 potential reserves for background monitoring. The geographical distribution of these reserves is shown in Figure 1. In general, they represent a good pattern of global distribution.

The 41 reserves cover eleven of the fourteen potential biomes. Certain biomes are more heavily represented than others. The mixed mountain and highland systems zone has a large number of reserves. Other biomes with a relatively large number of reserves present are the tropical dry or deciduous forests and the subtropical and temperate rain forests. Final selection of biosphere reserves to be used in the Integrated Global Background Monitoring Network is still to be determined.

APPROACH AND DESIGN PRINCIPLES

Within the context of this paper, it is not appropriate to discuss many of the details of sampling and monitoring design for the Integrated Background Monitoring Network. Much of this work has been done and can readily be adapted to monitoring in background areas (Wiersma and Brown 1980, Wiersma and Brown 1981, Wiersma et al. 1979, Wiersma 1981[b], Davidson et al. 1985, Rovinsky and Wiersma 1986). However, it is important to outline the principles under which an integrated background monitoring network will operate. The five basic principles which follow will be discussed separately below:

1. The monitoring system should be *multimedia* (integrated).
2. A *systems approach* should be used to relate media and help understand possible interactions between pollutants and ecosystem parameters.
3. Multicompound analytical chemistry procedures to measure *pollutants* should be used where possible.
4. *Key ecosystem (biotic) parameters* should be measured.

FIGURE 1 Biosphere reserves potentially suitable for biosphere reserve monitoring.

5. *Quality assurance* techniques should be applied during all phases of the project.

Multimedia System

An ideal monitoring system should be able to trace a pollutant from a source to a sink or exit point. In most remote terrestrial areas the pollutant input to the reserve site is via the air route. Specific sources, while generally associated with man's activity, are in practice difficult to locate. Therefore, input should be measured at the background site in the form of atmospheric concentrations as well as dry and wet deposition. Output from most background sites will be streams and rivers draining the area, and the loss of pollutants via this route can be determined by sampling representative drainages.

The multimedia monitoring approach integrates readily with data on ecological processes which are collected during the monitoring activity. However, it is highly unlikely that pollutant-related effects in remote areas will be detected. The greatest value will be in establishing baselines and long-term trends and in helping to understand cycling of compounds in the studied ecosystem. In addition, if long-term changes in ecosystem parameters are noted, then a good pollutant data base coordinated with the ecosystem parameters exists.

Systems Approach

Munn (1973) stated that it is essential that GEMS be designed to allow interactions between media to be studied, permitting delineation of the pathways of biogeochemical cycling. This requires a systems approach and is as applicable to the design of a system for a remote site as it is to putting the entire GEMS system together. A promising technique for accomplishing this is the use of kinetic models. Theoretical bases and applications of these models have been described in detail by O'Brien (1979), Miller and Buchanan (1979), Barry (1979), Eberhart et al. (1979), Wiersma (1979), and Wiersma et al. (1984).

Pollutants (Abiotic Parameters)

Many compounds exist which have both natural and anthropogenic sources. Indeed, one of the objectives of the Integrated Global Background Monitoring Network is to establish reference levels which will help separate natural influence from man's influence. However, for simplicity, the term "pollutant" refers in this paper to any measured compound.

The selection of a limited number of pollutants to be measured in background areas has been recommended by many scientists concerned with monitoring systems development in these areas (Munn 1973, Task Force II: Committee on International Environmental Affairs 1976, Ad Hoc Task Force on GNEM 1970). Virtually all the suggested pollutants have potential for long-term transport. However, advances in analytical chemical techniques allow for reconsideration of this approach.

For example, trace element techniques for a variety of media are now multi-elemental (Jaklevic et al. 1973 and 1976, Dzubay and Stevens 1975, Alexander and McAnulty 1981, Kahn 1982). Multi-residue techniques for trace organics are currently available for most environmental samples. With these new procedures, prior definition of the pollutants to be monitored is no longer necessary. In addition, these new techniques provide us with a true early warning capability, albeit at a higher cost. *In situ* measurements are necessary for parameters such as pH, conductivity, O_3, NO_x, and SO_2.

Key Ecosystem (Biotic) Parameters

There is no unanimity of opinion on the array of ecosystem parameters that should be selected for study as part of a monitoring network, although extensive lists of parameters have been developed (Anon. 1980, Institute of Ecology 1979, National Science Foundation 1977 and 1978). However, general agreement does exist on the need for measures of nutrient cycling, productivity, and populations of selected species.

Selected species may either be dominant in the ecosystem or sensitive to pollutant perturbations. Parameters which meet these criteria include: litterfall or leaf fall (McShane et al. 1983[a]), tree growth, tree reproduction, tree mortality, changes in the compliment of foliage (e.g., years of conifer needle retention), and changes in the composition of the decomposer community. Sensitive species may be plants (e.g., some lichen species) or animals (e.g., some birds and small mammals) and their sensitivity may be reflected in their population structure or growth rates. A similar selection of parameters can be made in stream or lake ecosystems.

Ecosystem processes are a challenging aspect of any monitoring program. Background data must be developed for natural, unpolluted systems if it is not currently available. These data can then be used as a baseline against which other presumably polluted ecosystems can be compared.

The selection of specific parameters and sampling techniques is problematic. Ecosystems are a complex web of linkages, making it difficult to isolate the phenomena of interest in either the sampling or analytical phase of research. The possibility of observer effects is always present, especially since measurements are repeated over many years. Statistics of candidate ecosystem parameters are also critical (Hinds 1984). It is therefore necessary to select processes which are sensitive to subtle changes and have natural levels of variability which allow statistical detection of deviations from the norm (McShane et al. 1983^b, Hinds 1984).

Permanent plots are an important element in the ecosystem monitoring program. Monumented field sites are critical for accurate measurements of ecosystem or demographic processes. Sampling of permanent plots can also provide thorough descriptions of key community and ecosystem parameters (e.g., standing crops of organic matter) essential to measurement, or interpretation of parameters of more specific interest in the pollutant monitoring program. One scheme for establishing permanent sample plots is the reference stand system used at Olympic (Franklin 1982), H.J. Andrews (Hawk et al. 1978), and Sequoia-Kings Canyon Biosphere Reserves.

Quality Assurance

A complete quality assurance program should include organization and personnel, facilities and equipment, analytical methodology, sampling and sample handling procedures, quality control, and data handling. The quality assurance program for the Integrated Global Background Monitoring Network ultimately must incorporate all of these elements to help ensure data comparability among sites.

THE INTEGRATED GLOBAL BACKGROUND MONITORING PILOT PROJECT

At a series of United Nations interagency and expert group meetings in Geneva and Nairobi, steps were taken to start an Integrated Global Background Monitoring Pilot Project (Anon. 1980). UNEP agreed to establish background integrated monitoring pilot sites in three biosphere reserves as part of the renewable resource monitoring component of GEMS and in cooperation with WMO and UNESCO. The reserves were to be located in Chile, the USSR, and the United States.

A tentative design for monitoring basic ecological processes as well as pollutants was established (WMO 1980), and a project was implemented initially in two biosphere reserves: the Torres del Paine National Park in Chile and the Olympic National Park in the United States. Thus, GEMS is now using the biosphere reserves as part of its terrestrial renewable resource monitoring program.

The pilot network has the following objectives:

- To develop a strategy and guidelines for global integrated background monitoring (site selection, sampling programs, sampling procedures, parameters monitored, data reporting and handling, etc.) on a routine basis, using the most cost-efficient approaches;
- To establish reference levels for pollutants that have already produced low-level, global contamination;
- To establish baseline levels for selected ecosystem parameters against which data from more polluted areas can be compared;
- To serve as an early warning system for detecting long-range transport of pollutants and changes in ecosystem processes.

In the USSR, there have been many activities in the area of background integrated monitoring. Rovinsky and Buyanova (1982) describe 22 background locations in the countries of the Council for Mutual Economic Assistance (CMEA). Rovinsky et al. (1982) also describe three sites within the USSR at which integrated background monitoring is taking place: Borovoye, Berezinskiy, and Repetekskiy. Rovinsky et al. (1983) reported on background monitoring in the Berezinskiy biosphere reserve and describe the sampling locations, monitoring program, and results from 1980 to 1982.

The projects in Chile and the United States are dependent upon available funding. The data sets collected in Torres del Paine National Park (Chile) and Olympic National Park (United States) will be integrated using the systems approach previously described.

Torres del Paine National Park

At Torres del Paine National Park, a Strohlein 150 high volume air sampler is being operated according to WMO specifications. Sampling times are for alternate 10-day intervals. Samples are analyzed for Al, Cd, Cu, Pb, and Zn. A GMWL high volume air sampler is operating in parallel with the Strohlein 150. A low volume, solar powered air monitor is also operating and samples are analyzed for the same elements.

Only wet deposition samples are collected. Dry deposition samples are planned although sampling will not be implemented until a standard, internationally accepted, dry deposition sampling procedure is developed. Two wet deposition samples are operating at the park. One is a two-bucket Aerochem sampler operated by the Global Precipitation Chemistry Project. The second sampler is an Erni automatic one-bucket sampler. For the first year of the study, samples from both devices will be analyzed by the Global Precipitation Chemistry Project. In the second year, samples will be split between the International Atomic Energy Agency (IAEA) laboratory in Vienna and the Global Precipitation Chemistry Project. A DeSaga automatic impinger sampler, prepared for sampling SO_2, has also been installed.

Water samples are collected monthly from the Chorillo Zapata, a stream draining the watershed containing the reference stand. Moss and lichen samples are collected twice a year, and soil and forest litter samples are collected yearly in the reference stand located just west of the major cordillera in the park. Samples are analyzed presently for 20 to 30 trace elements using spark source emission spectroscopy and inductively coupled plasma emission spectroscopy.

The reference stand is a mature lenga stand (*Nothofagus pumilio*). It was selected to be representative of the characteristics of mature lenga stands in the area. Detailed ecological studies are currently being conducted by researchers from the University of Chile. These studies include characterization of the reference stand to species, age and size classes and standing biomass, an overall vegetation inventory for the park, and studies on litter decomposition and turnover rates.

Recently, specialized studies were undertaken to measure SO_2, NO_2, and total oxidant levels in the park. A quality assurance program has been instituted for this project. Weather parameters are also measured in the park.

Olympic National Park

At Olympic National Park, a low volume air sampler has operated in the Hoh River Valley. A high volume air sampling station will be established when funds are available at a site yet to be determined. Siting is critical to avoid local contamination from slash burning, campfires, and parking lots. Analyses will be the same as for Torres del Paine National Park, with the addition of nitric acid in the high volume air samples. Sampling periods are approximately the same as for Torres del Paine National Park. It is also planned to eventually sample SO_2, NO_x, and O_3.

As in Chile, dry deposition measurements are not being made at this time. Wet deposition samples are being collected at a National Atmospheric Deposition Program (NADP) sampling station at the Hoh River Ranger Station. Also as in Chile, water, soil, forest litter, and moss samples are being collected. Analyses are carried out for trace elements by spark source emission spectroscopy and inductively coupled plasma emission. In addition, priority pollutant scans for approximately 100 organic compounds have been made on the soil, litter, and vegetation samples. Water samples are collected from a stream draining the area.

The reference stand is primarily a Sitka Spruce/Western Hemlock ecosystem. The stand has been characterized for standing and down biomass, species composition, and age and size classes. Specific studies on six ecosystem parameters are being measured: lichen productivity, moss productivity, leaf litter fall, litter decay rates, nutrient flux in soil, and needle population structure. In addition, a significant study by the University of Washington is underway on nutrient cycling on a watershed basis in the same area.

A quality assurance program has been instituted for this project. Weather parameters are being collected at the park and within the stand and are also available from the US Weather Service Station at Quillayute.

CONCLUSIONS

Experience in integrated monitoring of Biosphere Reserves and examinations of criteria for background monitoring and for characteristics of existing Biosphere Reserves lead to the following conclusions:

- An integrated global background monitoring network for pollutants and ecosystem processes should be established.
- Pollutant measurements should be made simultaneously in a number of environmental media.
- Cross-correlated ecosystem parameter studies should be carried out simultaneously with pollutant measurements.
- Monitoring in the proposed international network should be continuous and open-ended.
- The proposed network should consist initially of sites chosen, as appropriate, from the international MAB Biosphere Reserve System.
- The network should be under the overall coordination of the Global Environmental Monitoring System (GEMS) of UNEP, and, as such, it should be operated in close cooperation with the WMO Background Air Pollution Monitoring Network (BAPMoN). Other international agreements such as the US-USSR environmental agreement can also play a significant role.

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Issues in the Design of Monitoring for Global Change

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The world scientific community in general—and researchers in the United States and the USSR in particular—have a long record of successful collaboration in large-scale observation and data synthesis activities. Collaborative analysis of global weather patterns has continued systematically for 300 years (1), and work on ocean currents and high latitude ice flow has been carried out for only a slightly shorter period. Recently the United States and the USSR have participated in large-scale studies within international research programs such as the International Geophysical Year (IGY), the International Biological Program (IBP), and the Global Atmospheric Research Program (GARP). In addition, several joint reports are an important result of bilateral studies of northern oceans and shared marine resources (2).

What more is needed, then, in considering proposals for systematic study of global change? The goal for the next decade should be two-fold: first, to reach beyond earlier interdisciplinary and single discipline approaches to a degree not previously possible; and second, to extend measurement programs to emphasize fluxes of materials rather than concentrations within and among the earth's subsystems with a precision which could not be considered until now. These new approaches will require a restructuring of the basis for global change studies—particularly the scientific consensus-building process—in order to surpass previous experiences and take the initial steps toward setting priorities for global monitoring. A process for dealing constructively with these issues is the subject of this paper.

MODELING AS A GUIDE TO OBSERVATIONS AND MEASUREMENTS

Observations and measurements represent the classical basis of scientific discovery; reasoning from physical principles—now called modeling—is a more recent means of discovery. The greatest scientific advances of this century have used theory and modeling to guide critical measurements on systems either too small, too large, or too complex to observe directly. Carefully planned heuristic observations or data continue to be needed; in the US-Canadian measurements on the Great Lakes, for example, such programs have been classified as "surveillance" rather than monitoring (3).

For large-scale environmental systems, the most mature example of using modeling interactively with measurement technology on land, on the sea, and from space was the initiative of ICSU/WMO in planning GARP in 1968–69 (4). The plan was characterized by a "dialogue between modelers and technologists," an iterative exchange between those who study the system's dynamics (and who may specify needed spatial resolution and accuracy) and those who design and operate measurement capabilities and answer questions of technical feasibility or cost. Many issues were examined and conflicts were resolved during the GARP planning, even in advance of delivery of some of the remote sensing capabilities. The results in terms of capability to advance our understanding of global circulation have proven quite satisfactory. The study is an eighteen-year veteran model that should be reconsidered in light of the requirements of the International Geosphere Biosphere Program (IGBP).

Research over the last twenty years which has attempted to document a balance in the exchanges of carbon should also be considered. The "missing carbon" was discovered several decades ago, a finding based on either inadequate models or incomplete data—or both, as is more likely. Atmospheric, oceanic, and biospheric models directed a search for better resolution of discrepancies in all aspects of carbon sources and sinks. One discrepancy identified nearly ten years ago involved assumptions made in the West on forest carbon storage in the USSR without current data from the USSR; however, that problem has been gradually resolved.

As the carbon modeling group in the USSR and others have shown, the carbon cycle is more nearly balanced now (5). Still, the scientific community has begun to recognize problems derived from viewing the earth's carbon exchanges over recent decades as an equilibrium system, which it clearly is not. The research community is now faced with several tasks: to determine the rate of change in biospheric sources and sinks, as well as in anthropogenic sources; to identify associated uncertainties in understanding carbon cycles; and to ascertain whether still imprecise measurements of pools and fluxes of carbon limit the ability to answer questions concerning trends in carbon dynamics. Still, the experience with the iterative process that links modeling and measurements has been positive and illustrates how some of the issues affecting plans for global monitoring can be resolved.

CHARACTERIZATION OF GLOBAL SYSTEMS AND SUBSYSTEMS

The previously cited examples of how modeling leads to definition of needed measurements assume that the earth's atmosphere is a well-mixed system, and that differences due to latitude or to ratios of land and water surfaces can be incorporated within the parameters of a single macro-system. However, research results for several apparent environmental alterations involving human influences show that these problems tend to be regional, not global, in scope. Examples of this include dessication of resources in sub-Saharan Africa; oxidant and acidity influences in eastern North America and Europe; water quality and fishery impairment in the Baltic Sea and in other semi-enclosed marine ecosystems; and desertification of the mid-latitudes on all of the continental land masses.

A principal concern in the arid regions of China is the increase in salt aerosols arising from the recently dessicated and now dry salt lakes of Soviet Kazakhstan, a trend which has been documented by Soviet scientists. Chinese scientists fear that this regional environmental trend will increase salinization of soils in western China, and they recognize that the problem is regional rather than local.

The problem of transported acidity in regional environmental systems has been addressed previously. All of these regional problems involve alteration of chemical or hydrologic source terms, alteration of the geographic scope of sinks and of atmospheric transport, and long-term changes in the relationships among the major media: air, water (including biota), and land (including soils and biota). In this respect, regions where major environmental changes may be taking place have system characteristics which are essentially similar to those of the whole-earth systems considered previously.

A major issue for global monitoring in the view of many scientists is whether regional-scale questions should be dismissed as negligible at the global scale or whether methods of hierarchical modeling can be used to simultaneously investigate both regional and global-scale phenomena. The work of O'Neil et al. and others investigating hierarchically linked environmental properties could be used to determine whether understanding of global change can be improved through hierarchical monitoring and modeling instead of through single-level systems (6). Working groups should be established to investigate ways to resolve the issue of whether measurements in the IGBP should address principally whole-earth systems or whether the earth should be viewed as a system of hierarchically linked subsystems.

CHOOSING SIGNIFICANT VARIABLES: AIR, WATER, AND LAND SYSTEMS

Air

The atmosphere is the system for which the most fully validated models exist, and there is a general consensus on appropriate subjects of and methodology for measurements. However, new programs have recently been initiated on air chemistry in the troposphere and the stratosphere in an effort to understand factors controlling the dynamics of the high altitude ozone layer, and these programs indicate the need for improved measurements and models. Vitally important are several trace gases in addition to chlorofluorocarbons (CFCs), including nitrogen oxides and other by-products of everyday industrial and agricultural practices. A global emissions inventory is urgently needed for all of these substances, including those partially of natural origin, along with estimation of sink strengths. However, a full consensus does not yet exist regarding even the list of gases to be studied.

Another emerging question is the source/transport/receptor relationship for persistent toxic substances volatilized into the air. Contamination of water resources through long distance atmospheric transport of substances originating on land is a prime example of the intermedia transport problem. However, the issue of source/receptor relationships for these substances primarily involves the air system. This is of special interest because small quantities of fresh inputs of toxics (e.g., DDT in Lake Superior before it has broken down into DDE) can now be detected in remote sites, indicating a point of origin thousands of miles away. It is becoming clear that quantification of the transport of these substances is needed from land to the various ocean systems, between continents, and over the northern frozen sea. The question of how many of the persistent toxic substances—such as how many metals—should be addressed in a study of global change remains an issue to be resolved through a consensus development process.

Water

Other papers have already addressed the problem of regional water quality alterations and trends that can clearly assume global significance. While quantitative approaches are being agreed upon for identifying key variables and the parameters needed to understand factors controlling change in aquatic environments, the elements of concern vary widely from one system to another. Specific problems include phosphorus and toxic substances in the Great Lakes of North America, in Europe, and in Asia; excess sulfate in poorly buffered lakes on both sides of the Atlantic; agricultural runoff into streams, rivers, and inshore marine ecosystems such as the Chesapeake Bay and Adriatic Sea; and metal mobilization such as the mercury problem in Lake St. Clair, the Baltic Sea, and coastal sites in Japan.

Excess nutrients are probably the most general vehicle for change in aquatic environments. However, local contamination by persistent organic substances, metals, or acidification may be of equal or greater significance for long-term resource utility. Consensus is needed to determine which, if not all, of these variables are appropriate for a program of monitoring for global change.

Land

In the terrestrial environment, the variables most frequently cited as having global significance are those describing changes in land use, particularly as they influence solar absorptivity and hydrology. Also important, however, are the changes induced by runoff of soils and chemicals, soil transport by wind, impairment of the productivity of the biotic land cover, and impoverishment of the diversity of life in ecosystems. Most of these variables are also of interest on a regional basis, e.g., deforestation, erosion and deposition, hydrologic diversion and irrigation, desertification, and biological impoverishment. All of these problems are commonly thought to be significant alterations of the earth's land systems which could affect atmospheric chemistry by adding some substances while failing to remove others. Through positive feedback, these processes have the potential to accelerate the effect of CO_2 and other trace gases on climate.

In northeast China, for example, desertification from overgrazing in Inner Mongolia is beginning to affect climate, forest productivity, and agriculture in the region. This complex interaction among terrestrial and atmospheric subsystems may be repeated several times over in other continents. The hierarchical modeling suggested earlier would help to determine the array of measurements needed in the land environment to document variability, short-term or long-term trends, and controlling factors for this part of the global change problem.

Also important for terrestrial monitoring is the network of biosphere reserves now developed in nearly 100 countries around the world through UNESCO's program on Man And Biosphere (MAB). Over 200 sites are currently available. Especially valuable is the comparative measurement and synthesis that have been done in the past between US and Soviet scientists. This cooperation between the two countries needs to be renewed and expanded to include the many other countries around the world that participate in MAB and hope to be involved in an IGBP.

TOWARD RESOLUTION OF MEASUREMENT ISSUES

As the scientific community seeks consensus on how to measure trends in the earth's environment and determine which research questions deserve the highest priority, many differences will arise in seeking agreement on measurement methods and procedures for detecting change over time and distance.

The issue of what constitutes the core set of priority questions may require proceeding simultaneously with an active level of modeling and measurement and a series of international study groups and conferences to determine which problems are local as opposed to actually (or potentially) global (7). The result will probably be pragmatic accommodation among research groups addressing unique regional questions within higher-order global data synthesis and modeling questions. Until understanding of processes controlling linkages at the regional and global level is improved, global synthesis is less likely to accurately determine the variables or parameters that should be measured or to define the precision of such measurements. Many aspects of these issues will be resolved if there is consensus reached on modeling approaches, but that too will take time and a high level of commitment on the part of the countries and scientists involved.

To the extent that mass balance modeling may be a part of the larger scheme, detailed documentation of emissions or other estimators of source terms will need to be agreed upon as part of the monitoring. Measurements of residuals in the various media—air, water, and soil—may be straightforward if agreement on precision can be obtained. However, differences in instruments and laboratory procedures between countries and across continents pose obstacles that can only be resolved with time. The problem of determining the ultimate sinks of substances involved in global change (even CO_2) is likely to remain one of the most difficult problems.

Steps are currently being taken toward resolution of lead-time modeling and related measurement questions through the various study groups of the International Council of Scientific Unions (ICSU) and its subdivisions; through UN agencies; through national committees of the National Academy of Sciences; and through bilateral arrangements such as this symposium. Still, much more is needed to achieve a full exchange of experience and recent results between scientists around the world who are, at least locally, investigating change in the earth's systems.

The issue of which types of subsystems to model in the near term (e.g., atmosphere or oceans; or sulphur, nitrogen, and toxic substances in intermedia exchanges) may be resolved by priority questions implicit in the models cited earlier. The best developed models—those of the earth's atmospheric systems—may already determine the perception of these major questions. Beyond these first steps in modeling, however, measurements are needed to assure that the modeling approach does not lead to excessive resolution beyond what is essential for regional or global dynamics, or to oversimplification whereby important questions are removed in the initial system abstraction.

Modeling methods vary widely within and between countries, and there may well be no single best method. For this reason little agreement may be found initially on the significance of measurements indicating global change. Agreement concerning the strengths or weaknesses of parameter estimation and computer code conventions should be an integral part of preparation for measurements.

Finally, there is the issue of possible new approaches to measurements and modeling, particularly the incorporation of space-based monitoring (7). Progress on these issues probably cannot wait for complete direction from the national governments. However, those scientists who pursue individual initiatives must accept the need for both national and multinational coordination, as well as for a final accommodation after all methods proposals have been duly considered. The planning framework for such coordination currently exists, and bilateral or other group initiatives are both possible and desirable as long as national committees for the IGBP are kept informed. A range of consensus-forming processes should be viewed as contributing to enrichment of the potential to study global change systematically and precisely. The dialogue begun at this symposium presents an opportunity for further resolution of the global measurement issues which may presently divide scientists in the United States, the USSR, and elsewhere.

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Appendix 1

List of Participants

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Appendix 2

Protocol of the Fifth US-USSR Symposium on Comprehensive Analysis of the Environment

Washington, USA
December 10–13, 1987

In accordance with the memorandum of the Ninth Session of the Joint Soviet-American Committee on Cooperation in the Field of Environmental Protection, within the framework of Project 02.07-21, the Fifth Soviet-American Symposium on Comprehensive Analysis of the Environment was held in Washington, DC, December 10-13, 1986. Co-chairing the Symposium were Mr. L.M. Thomas, Administrator of the Environmental Protection Agency of the USA, and Dr. Y.A. Izrael, Chairman of the State Committee for Hydrometeorology and Control of the Natural Environment and corresponding member of the Academy of Sciences of the USSR.

Presented at the Symposium were 24 papers in which US and USSR scientists described the present ecological situation on the global scale as well as in their own countries, and defined the principal problems of negative geophysical and ecological consequences of anthropogenic effects on the biosphere and permissible loadings.

The reports and discussions centered on concepts of the stability of natural systems, the assimilative capacity of natural ecosystems, and the biogeochemical cycles of chemical elements and mass balances. Theoretical and practical aspects of monitoring natural resources were discussed. The Symposium stressed the importance of mathematical modeling for solving the problems of assessing and predicting anthropogenic changes in the state of ecosystems, and the relationship between monitoring data and

modeled calculations. The problem of long distance atmospheric transport and transformation of pollutants was emphasized.

The papers of Symposium participants dealt with the current ecological situation in the following major areas: *(1)* basic scientific approaches and concepts; *(2)* monitoring methodologies and their application; *(3)* regional-scale case studies, including the hazard of the long-term effects upon the ocean of small doses of stable pollutants in which the value of comprehensive ecological monitoring of the world ocean was underscored; *(4)* management applications; and *(5)* global monitoring strategies.

The Symposium participants discussed the results of the second US-USSR Bering Sea Expedition conducted in 1984 on board the scientific research vessel *Academician Korolev*, as well as the results of a US-USSR experiment conducted in 1983 on the same vessel to study gases capable of affecting climate. The long distance transfer of pollutants and questions of the anthropogenic impact on the soil surface and the functioning of soil biocenoses were particularly stressed.

Symposium participants agreed that progress has been made in the understanding and substantiation of many of the above problems and issues, as well as in the practical application of research results, including the development of monitoring, the use of comprehensive indicator systems, and greater standardization in ecological approaches in both countries.

As a result of the Symposium work, the participating scientists confirmed that the principal questions to be studied within the framework of this project are:

- **Scientific substantiation of monitoring anthropogenic changes in the environment, including observation, analysis, and forecasting of this state;**
- **Ecological aspects of such research, including identification of ecological consequences of pollution and assessment of ecological risk from such effects;**
- **Developing a scientific base for monitoring in all media, taking into account multi-media pollutants, and including the monitoring of land ecosystems;**
- **Developing the study of the chemical pollution of the ocean ecology and the ecological consequences of anthropogenic pollution;**

- Determining the role of monitoring in the system of environmental and economic decision making;
- Introducing ecological assessments into the evaluation of damage to and degradation of the natural environment and resources resulting from anthropogenic activity, and development of ecological/economic modeling to this end;
- Further work to develop ecological standards and norms.

Both sides agreed to publish the Symposium proceedings in English and Russian in 1987.

The project co-chairmen and the Symposium participants have agreed that within the framework of the project, continued attention will be given to current global problems such as: possible climatic changes, risks from stratospheric ozone layer depletion, contamination of the world ocean, acid rain, total assessment of the global state of the environment, and development of approaches to implement such an assessment. It was deemed desirable to develop a joint US-USSR program of research and comprehensive ecological monitoring for specific locations of the open ocean. To this end, the Soviet side will prepare a proposal for joint consideration.

The co-chairmen have agreed that the Comprehensive Analysis of the Environment project will serve as a synthesizing and coordinating project to provide a framework for conducting integrated analysis of all the information obtained both within this and other projects of this Agreement.

Both sides note with satisfaction that the Symposium was conducted in a spirit of close cooperation and has proven mutually useful. Soviet scientists express their gratitude to the US delegation for organizing the Symposium and the warm hospitality accorded the visitors. The US and Soviet delegations also express their appreciation to the National Academy of Sciences for its hospitality and support in conducting the Symposium, and to the MacArthur Foundation for its support. Both delegations also thank the interpreters and technical staff for their excellent work.

This protocol was signed in Washington, USA, on December 15, 1986, in English and Russian, both texts being equally authentic.

L.M. Thomas

Chair, USA Delegation
Administrator, US Environmental Protection Agency

Y.A. Izrael

Chair, USSR Delegation
Chair, USSR State Committee for Hydrometeorology
and Control of the Natural Environment
Corresponding Member, USSR Academy of Sciences