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**SPECULATIONS ON THE CONSEQUENCES TO  
BIOLOGY OF SPACE SHUTTLE-ASSOCIATED  
INCREASES IN GLOBAL UV-B RADIATION**

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**January 1977**



**(NASA-TM-X-73200) SPECULATIONS ON THE  
CONSEQUENCES TO BIOLOGY OF SPACE  
SHUTTLE-ASSOCIATED INCREASES IN GLOBAL UV-B  
RADIATION (NASA) 17 p HC A02/MF A01**

**N77-18728**

**Unclas  
CSCL 06R G3/52 16332**

1. Report No. NASA TM X-73,200	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle SPECULATIONS ON THE CONSEQUENCES TO BIOLOGY OF SPACE SHUTTLE-ASSOCIATED INCREASES IN GLOBAL UV-B RADIATION		5. Report Date	
		6. Performing Organization Code	
7. Author(s) M. M. Averner and R. D. MacElroy		8. Performing Organization Report No. A-6896	
		10. Work Unit No. 199-43-02-01	
9. Performing Organization Name and Address  Ames Research Center, NASA Moffett Field, Calif. 94035		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address  National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code	
		15. Supplementary Notes	
16. Abstract  Space shuttle launches can cause depletion of stratospheric ozone through interaction with exhaust gases. Various aspects of the impact of ozone depletion on the biosphere are assessed and discussed. Speculations on the factors which may determine the extent and nature of biological damage due to an increased flux of ultra-violet light are presented. It is concluded that a complete assessment must consider both direct effects (organisms) as well as indirect effects (ecosystems). The role of computer simulation of ecosystem models as a predictive tool is examined.			
17. Key Words (Suggested by Author(s))  Ozone UV-B Space shuttle Ecosystem modeling		18. Distribution Statement  Limited - Available from Originating Office Only  LSTAR Category - 52	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 17	22. Price* \$3.25

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SUMMARY

Increases in the concentration of a number of chemical pollutants in the atmosphere as a consequence of human activities, including the space shuttle program, may lead to a decrease in the global mass of ozone. This depletion of ozone could allow an increase in the flux of solar ultra-violet radiation incident on the surface of the planet. Because certain wavelengths of ultra-violet are harmful to biological processes this increased flux of UV will have an unknown but potentially harmful effect upon the biosphere. There is a need to accurately assess the extent of biological damage which might arise as a function of fractional changes in the global ozone mass. Much effort is being expended in evaluating the *direct* effects of increased UV radiation on plant, animal, and microbial species, but little attention has so far been focused on the *indirect* effects. An assessment of these indirect effects may be critically important in evaluating the total impact on increased global UV flux. Each species is a member of a more or less complex ecosystem. As a particular species might be adversely affected by increased UV radiation, so the ecosystem of which the species is a part will also be adversely affected. Thus, the initial direct damage will be amplified and extended. Only an understanding of ecosystem dynamics and the mechanisms by which UV light can affect the components of the ecosystem will allow a complete assessment of the potential biological impact of increased radiation resulting from inadvertent ozone depletion.

THE PROBLEM

The Sun radiates electromagnetic energy over a wide range of wavelengths including the ultra-violet, visible, and infrared regions. The ultra-violet (UV) portion of the solar spectrum contains wavelengths that are biologically harmful (BHUV).<sup>1</sup> That life exists on the planetary surface is due to the presence of ozone in the stratosphere. Ozone absorbs UV light and the absorption spectrum of ozone includes precisely those wavelengths which are biologically most harmful. Thus, the solar radiation incident on the surface

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<sup>1</sup>The term BHUV is often used interchangeably with the term UV-B which refers to the UV region between 280 nm-320 nm.

of the planet is greatly attenuated in that spectral region which is most harmful to biological processes. While the actual flux of BHUV at the planetary surface is a function of a number of parameters (Rayleigh scattering, reflection and attenuation by water vapor, clouds, haze, and smog, etc.), a decrease in the atmospheric mass of ozone will cause an increase in BHUV surface irradiation with accompanying harmful biological effects.

There are a number of human activities which release chemicals into the atmosphere. Some of these chemicals have the potential of increasing the rate of destruction of atmospheric ozone. One of these chemicals (HCl) is released during the burning of the solid propellant used during lift-off of the space shuttle. Thus, the question has arisen of what might be the biological effects of any increase in global BHUV which might be caused by the space shuttle program.

While the relationship between fractional changes in ozone mass and increased BHUV flux can be mathematically modeled with some degree of accuracy, projecting the nature and extent of biological harm which could result from such increases in BHUV with equal accuracy is, at this point, impossible. This report is directed at a discussion of certain aspects of the strategy and tactics of developing a model of the relationship between surface BHUV flux and biological processes for the purpose of more accurately projecting the expected consequences to biology of decreases in the mass of atmospheric ozone.

#### THE RULES OF THE GAME

As part of an assessment of the potential environmental impact of the supersonic transport, the department of transportation funded a study of the climatic changes which might result from perturbation of the upper atmosphere by the exhaust effluent of a global high-altitude aircraft fleet (ref. 1). This program, the Climatic Impact Assessment Program (CIAP), resulted in an exhaustive review of the state of knowledge of the effects of BHUV on the biosphere. Reproduced below are the major conclusions of this study:

1. With a partial reduction in atmospheric ozone, UV-B irradiance at ground level will increase. Although this increase does not represent a large increase of radiant energy flux, the biologically effective UV-B irradiance would increase at a greater rate than anticipated for total UV-B radiant energy flux.

2. Excessive UV-B radiation is a decidedly detrimental factor for most organisms, including man. Even current levels of solar UV-B irradiance can be linked with phenomena such as increased mutation rates, delay of cell division, depression of photosynthesis in phytoplankton, skin cancer in humans, cancer eye in certain cattle, and lethality of many lower organisms such as aquatic invertebrates and bacteria.

3. Experiments with supplementary UV-B irradiation, simulating a substantial ozone reduction, have shown that the increased UV-B irradiance enhances the detrimental effects mentioned above and also causes a reduction of growth and photosynthesis in higher plants, inhibition of pollen germination, aberrations of insect and amphibian growth and development, and shifts in the community structure of aquatic microcosms.

4. Epidemiological data for skin cancer of Caucasians have been used to evaluate the expected rate of the increase of skin tumors due to reduction of ozone. An approximate 2 percent increase of skin cancer incidence is anticipated for each 1 percent reduction of mean atmospheric ozone. The uncertainty associated with the 2:1 ratio is, however, very great.

5. It is apparent that organisms exposed to solar radiation have evolved strategies to cope with current levels of UV-B irradiance. These include minimizing the impingement of UV-B radiation of physiological targets through filtration of the radiation by cellular pigments or by outer tissue layers, behavioral avoidance, and various radiation repair mechanisms.

6. Within any class of organism, there is apparently a substantial variation in basic sensitivity to UV-B radiation, probably related to variation in efficacy of tolerance mechanisms.

7. The UV radiation dose-response relationships of most organisms are quite nonlinear and, in some cases, with pronounced dose rate dependencies. Because of this nonlinearity, it is difficult at present to predict whether or not most species have sufficient capacity to tolerate an increased UV-B radiation load.

8. The capacity of organisms to evolve a heightened resistance to increased solar UV-B irradiance within the relatively short time when this perturbation could be effected (ca. 20-30 years) is difficult to predict. It is, however, quite unlikely that many species could undergo this evolution in such a short time span.

9. In addition to the direct impact of solar UV-B radiation on organisms, many subtle and indirect effects may also impact both agricultural and nonagricultural ecosystems, such as slight alterations in competitive balance or resistance to herbivores or disease organisms.

10. Despite the complexity involved in assessment of the potential impacts of increased solar UV-B radiation on the biosphere, this preliminary analysis has provided a useful start. A modest, incisive, and well-designed research effort over the next several years may well yield a reasonable perspective with which to evaluate quantitatively the biological implications of various degrees of atmospheric ozone reduction resulting from anthropogenic sources.

In March 1976, a Space Shuttle Environment Assessment Workshop on the Stratospheric effects of Space Shuttle exhaust was held at NASA/Johnson Space Center (ref. 2). A then-current assessment of the biospheric impact

of UV radiation increase resulting from ozone depletion was presented (ref. 3). Assuming a worst-case situation of 1 percent ozone depletion and a 2 percent increase in BHUV radiation, the following conclusions were reached:

1. The effects on the biosphere of a 2-percent increase in BHUV radiation will not be detectable with decades of observation because the natural fluctuation of BHUV radiation and the ecosystem are so much larger than this increase. These fluctuations include (a) greater variability of BHUV irradiances; (b) statistical uncertainty involved in the response of organisms and ecosystems to given doses of BHUV radiation at given dose rates; and (c) larger normal variation in the response of organisms to other, more pervasive or important, environmental factors to which they are exposed — factors such as temperature, moisture, nutrition, competition, and predation. However, just because a cause-and-effect role of an increase in BHUV radiation cannot be statistically detected, this does not mean that an increase in BHUV radiation can be ruled out as a contributor to some deleterious future event. Lack of detectability is not equatable with a lack of effect.

2. There is a very low probability that an average 2-percent increase in BHUV radiation will have any unacceptable effect on agricultural plants or natural ecosystems, independently of whether the effects of such an increase are detectable or not.

3. There may be some increase in the number of melanoma and nonmelanoma skin cancer cases among susceptible individuals resulting from 1-percent  $O_3$  depletion, but it will not be detectable because of (a) the natural variations of BHUV radiation and biological variability mentioned above, (b) the long latent period (20 to 60 years) for induction of skin tumors, and (c) the many other factors that already may be tending to increase or decrease the number of reported skin cancer cases. Factors possibly leading to an increased number of melanoma cases in the United States include (a) the increased proportion of people in the population living long enough to contract skin cancer, (b) increased reporting of skin cancer cases because of Medicare; (c) the changing life style of people, which in recent years involves more leisure time activity in the sunshine; and (d) the net southward migration of the population. (Regarding the latter factor, between 1940 and 1970, the center of population of the United States moved west and approximately 35 miles south from a latitude of about  $39^\circ N$ ; this amount of southward latitude movement corresponds to a 2-percent increase in the annual dose of BHUV radiation). Factors possibly leading to a decreased incidence include action based on publicity-induced recognition by the population of the dangers of overexposure to solar radiation and on more accurate identification of susceptible individuals as a result of research generated by the  $O_3$  depletion problem.

4. The number of skin cancer cases resulting from a 1-percent  $O_3$  reduction is not realistically predictable. (This is true despite the very widely quoted prediction that a 1-percent decrease in stratospheric  $O_3$  will lead to 6000 more cases of skin cancer each year in the United States alone). The extant experimental and epidemiological data, although clearly suggesting

some contribution of solar radiation exposure to skin cancer incidence, are inadequate for making quantitative predictions within reasonable limits of uncertainty.

A major conclusion drawn from these studies is that available techniques and data are inadequate for accurately predicting the biological effect of the small increases in UV surface flux expected as a result of space shuttle operations. In the absence of precise information one can only speculate. The following remarks are in this spirit and are expressly stimulated by and addressed to the current NASA assessment of this problem.

*Point 1. What degree of damage to biological processes might be expected as a consequence of projected space shuttle operations?*

There seems to be little or no evidence that the projected space shuttle program will result in catastrophic direct effects on the biosphere. A more controversial question concerns the results of long-term exposure to small increases in BHUV on the productivity, structure or stability of ecosystems through indirect effects. The accumulation of relatively small changes in such processes as photosynthesis, pollination or cellular respiration can result in large changes in ecosystems through mechanisms such as competition for food or niche selection. The NASA assessment speculates that there is a very low probability of a 2-percent increase in BHUV having any measurable effect on plants or ecosystems. This conclusion is based upon the fact that many organisms can tolerate unnaturally high levels of BHUV or, if vulnerable, have evolved strategies for coping with the levels of BHUV currently irradiating their environment. Presumably these strategies would be capable of absorbing the anticipated moderate increases in BHUV caused by the space shuttle program.

This would be true only if the mechanism or strategy of BHUV protection is 100 percent effective and there is a "protection reserve," or capacity to absorb the extra BHUV. If exposure to current levels of BHUV causes biological damage to an organism, albeit reduced due to the presence of a protective mechanism, then the organism is at some non-zero point in its BHUV dose response curve. That is, the protective mechanism the organism has evolved is not effective enough to afford complete protection against current levels of BHUV. The protective mechanism is "leaky." In this case, an increase in the dose of BHUV will cause an increase in biological damage. That such "leaky" protective mechanisms occur is indicated by the finding that the photosynthetic productivity of naturally occurring populations of marine phytoplankton is suppressed by present levels of BHUV in their environment and can be increased when shielding is supplied (ref. 4). It is reasonable to conclude that for these populations productivity would be even more suppressed if the flux of BHUV were to be increased. The distinction between the effect of BHUV upon population *number* and population *productivity* is a very important one. Probably the carrying capacity of few, if any, environments are limited by current levels of BHUV. Only those populations whose numbers are already limited by BHUV will decrease if present levels of BHUV are moderately increased. Those populations whose numbers are limited by some environmental factor other than BHUV (e.g., nutrients) will not suffer a reduction in size. As BHUV kills some organisms, more nutrients will be made

available and the population will increase in number until the carrying capacity of the environment is again reached. While there may be few populations whose numbers are currently limited by the BHUV incident on their environment, there may be many ecosystems whose productivity is being suppressed by current levels of BHUV. It would be expected that a further decrease in productivity may occur if BHUV is increased.

Physiological and behavioral defenses against UV radiation damage are energy demanding. The repair of damaged macromolecules, the synthesis of UV absorbing pigments and avoidance behaviors all require the expenditure of energy; energy that might have been utilized for growth or reproduction. An additional consideration is the possibility that while there may be little or no direct effect of increased BHUV flux on an organism or an ecosystem, such an increase may add to other environmental stresses already impinging on the ecosystem so that the combined effect might cause instability. The NASA Assessment weighs the question of whether damage to biological processes is proportional to the maximum single dose the process is exposed to or to the mean dose. It concludes that the maximum dose is the more important parameter. This is not true for those instances where the effects of BHUV are cumulative. In these cases, the extent of damage would be proportional to the total accumulated dose. Inasmuch as the mean dose is a measure of the total dose, then the extent of biological harm will be proportional to the mean dose and not to the maximum dose. While there may be biological effects of BHUV which are not cumulative, the incidence of UV-induced skin cancer in mice, and possibly in humans, seems to be proportional to the cumulative dose of UV (ref. 5).

*Point 2. What might be the effect of projected space shuttle operations on Agrosystems?*

The NASA Assessment discusses the probable effect of a small increase in BHUV on agrosystems. The analysis is based on experiments reported in monograph 5 of the CIAP report. Generally, these experiments measured the effects on a variety of plant species of chronic exposure to large doses of BHUV under a variety of growth environments: greenhouse, field, solarium and growth chamber. The results indicate that the effects of BHUV on plants are quite variable and a function of both variety and, interestingly, the growth environment. Generally, the plants show a lessened sensitivity to BHUV in the field as compared to more controlled conditions as in a greenhouse. There are no data on the effects of long-term exposure to low levels of BHUV (i.e., over several growing seasons). The Assessment concludes that either there will be no adverse effects on plant productivity from exposure to a 2 percent increase in BHUV or, in those plants that are sensitive, there will be only a fraction of a percent decrease in productivity. Key to this conclusion is the assumption, not totally unreasonable, of a linear relationship between BHUV dose and damage. As the experiments carried out for the CIAP program used rather high doses of BHUV, often corresponding to a 50 percent decrease in ozone, the effects of a more realistic 1 percent decrease must be extrapolated. This extrapolation results in an estimation of little direct damage to crop productivity. A major defect in the available data is the lack of a study of the effects of chronic exposure of single species or

plant ecosystems to small increases in BHUV carried out over a number of growing seasons. Such evaluation should include measurements of both seed production and viability, as well as of plant resistance to such environmental stress as drought and pests. The aforementioned differences in sensitivity of plant species grown in different environments to BHUV might be an indication of an important interplay between BHUV irradiation and other environmentally related physiological factors. Such modifying environmental factors must be understood before a more accurate assessment of BHUV-related biological damage can be made.

*Point 3. What might be the effect of projected space shuttle operations on the incidence of human skin tumors?*

The nature of this problem clearly makes it the most sensitive issue associated with the potential harmful effects of increased BHUV and one which will be given the closest public scrutiny and debate. The NASA Assessment concludes that any increase in skin cancer caused by a 2 percent increase in BHUV flux will not be detected. This is due to ignorance of the actual rate of skin cancer, natural variability in this rate and the lengthy latent period (20-60 yr) associated with UV-B caused skin cancer. There, as well, seem to be a number of factors in addition to BHUV radiation which determine skin cancer incidence; the present rate of nonmalignant skin cancer seems to be changing independent of changes in BHUV flux. While admitting "some contribution of solar radiation exposure to nonmelanomic skin cancer incidence...." The Assessment concludes that there is no way of making accurate quantitative predictions of the dose-related increase in cases of this disease. It is clear that much of the discussion of evaluating the biological impact of space shuttle centers on the distinction between the probability of *causing* harmful effects and the probability of *detecting* such harmful effects, coupled with the wisdom of proceeding with a program which will produce deleterious effects when the level of these effects cannot be accurately predicted. It is important to realize that while the actual number of additional cases of nonlethal skin cancer due to an increase in BHUV may not be detectable due to the low signal to noise ratio, this number is potentially quite significant. If the present annual rate of human skin cancer (nonmelanomic) in the United States is assumed to be  $\approx 160/10^5$  population (ref. 6), then a 2-percent increase in incidence would result in an annual rate of  $\approx 163/10^5$  population, that is, 3 extra cases/year/ $10^5$  population, or approximately 6000 extra cases/year/total population. Even if estimates for the current rate of skin cancer or number of extra cases are too high by 50 percent, a 2 percent-increase in BHUV might still produce several thousand additional cases per year. Granted that these additional cases could not be measured due to the natural variation of the very large and not well known annual rate of skin cancer, as well as the long latent period, they would still theoretically occur at some time.

Even worse, the potential number of additional cases becomes quite large when extrapolated for the global sensitive population and for the number of years that the increased level of BHUV might be maintained. Another example of the effect of multiplying a small number by a very large number is seen in a consideration of the effect of a 2-percent increase in BHUV on the

incidence of cases of lethal skin cancer (assuming the etiology of this disease is due to accumulated BHUV damage). CIAP estimates the death rate for all forms of skin cancer in 1967 to be  $16/10^6$  and increasing at about 4.5 percent/year (ref. 7). At the rate of  $16/10^6$ , and assuming an additional 2-percent increase due to increased BHUV, the number of additional mortalities due to increased BHUV might be in the order of 60/year. Integrating over the total sensitive global population and for a 10-year period during which the increased BHUV might be maintained, could result in a total increase of lethal skin cancer of several thousand. While these calculations are, of course, crude and involve simplifying assumptions, they nevertheless indicate that there may be potentially harmful consequences. Thus, every effort must be made to replace these crude and inaccurate approximations with more accurate data.

*Point 4. The question of the relationship of 254 nm and UV-B related biological effects.*

There exists a very large body of information on the biological effects of UV radiation. Most of this information, however, concerns the effects and mechanism of action of UV of wavelength 254 nm. The wavelengths of interest from the point of view of ozone depletion are 280 nm to 320 nm, the so-called UV-B region. It would be of enormous help to predictive studies if a relationship between the biological damage caused by exposure of organisms to 254 nm radiation and the damage caused by UV-B could be identified. If, for example, there were no qualitative differences in the damage caused by these two UV regions, then the problem of relating 254 nm damage to UV-B damage would be primarily a scaling problem. If such a relationship(s) were identified then the body of information available on the biological effects of 254 nm could be utilized. That there may be no *simple* relationship is indicated by Nachtwey's attempt to quantify the biological effects of UV-B by assuming a relationship between UV-B and 280 nm damage (ref. 8). This assumed relationship was established by combining published generalized UV action spectrum for the region 280 nm to 320 nm and the ratio of 254 nm to 280 nm biological effects as determined by an examination of published data. Predictions of the extent of UV-B biological damage calculated by this procedure were not verified when tested in the laboratory. No simple relationships between 254 nm damage and UV-B damage were apparent and indeed it may be that the mechanisms by which damage is caused by these two wavelengths are qualitatively different. Studies to establish the mechanisms and relationships of the biological damage caused by these wavelengths are of extreme importance and must be pursued.

*Point 5. On modeling the biological effects of ultra-violet radiation on homogeneous populations of organisms.*

The sensitivity of any species to UV radiation depends upon a large number of factors including behavioral and physiological protective or repair mechanisms, the wavelength dependency of the biological damage, and the intensity and time of exposure to the radiation. It is possible to incorporate these various factors into a mathematical model which could be used as a tool for predicting the degree of biological damage which might result from

a given increase in the UV irradiation of a given species. The values chosen for the above parameters could be varied to reflect the properties of different organisms and different mechanisms of UV damage. By this method the spectrum of responses which might be expected from the irradiation of different species could be visualized. Validation of the model could be carried out by empirical laboratory or field testing of specific organisms. The interplay between the theoretical mathematical model and test data would fine tune the model which then could be used for predictive purposes.

The accuracy of the mathematical model may be dependent upon our ability to incorporate into the model the very large body of data available on the biological effects of 254 nm radiation. Thus, the relationship between the 254 nm damage and UV-B damage must be clarified (see Point 4).

*Point 6. On modeling the biological effects of UV radiation on heterogenous populations of organisms (ecosystems).*

Quantifying the direct effects of UV-B on any single species is necessary for predicting the potential biological damage resulting from an increased UV flux. Of equal, or possibly greater, importance is quantifying the indirect effects; alterations in the ecosystem of which the UV-B sensitive organism is a part. Organisms live through interactions with other organisms, and all are part of a complex system of interdependencies. Any alteration in the number, activity, or productivity of one species can cause, by a variety of mechanisms, changes in other species which themselves may not suffer any direct UV effects. For example, any reduction in numbers of the pelagic oceanic plankton would have effects upon the entire food net of which the plankton is a part. The importance of these indirect effects cannot be overestimated. Unfortunately, the lack of knowledge of the behavior of large ecosystems and the difficulties in studying them are very great. Despite these limitations the role of UV-B in influencing the structure, stability, composition and productivity of those ecosystems believed to be effected by an increase in global solar UV radiation must be evaluated.

While there are a number of valid approaches to such a study, and indeed a precise and accurate model can only come out of an integrated study in which all of these various approaches are utilized, we feel that computer simulation of ecosystem dynamics based upon presently available ecosystem models may be a uniquely valuable tool.

## THE USE OF COMPUTER SIMULATION TO PREDICT THE BEHAVIOR OF ECOSYSTEMS

### Background

Plants and animals living together, plus that part of their physical environment with which they interact, constitute an ecosystem. Many opposing forces operate within a natural ecosystem, for example, organisms live and die, moisture and nutrients travel out of the soil and are returned to it. Furthermore, many of these interactions and oppositions are exquisitely

protected from major disruptions allowing relatively permanent and stable ecosystems. During a dry season, for example, when the mice in a grassland have less food, their birth rate decreases. Another behavioral response is to retreat to their burrows and thus their death rate due to predation also decreases. This behavior protects not only their own population but that of the grasses as well. The lack of moisture inhibits plant growth but inactive animals consume less grass. There is a tendency for ecosystems to maintain their existence by appropriate opposition of processes and by regulatory mechanisms which protect these processes against disruption. Over the millennia, evolution has selected mechanisms which allow for the survival of ecosystems in the face of such stresses as migration, drought, flood, fire, or frost. However, while ecosystems are qualitatively stable against moderate environmental fluctuation, the quantitative aspects of the ecosystem will fluctuate in concert with the environmental fluctuations. Thus, in the above example, the period of drought will result in less productive fields, proportionately fewer young mice and a smaller population of predators. The compensatory mechanisms do not prevent change; rather, they tend to buffer the amount of change and allow the ecosystem to go back to its original state once the stress is removed. If, however, a stress to an ecosystem is large enough the compensatory mechanisms may be overridden and more drastic changes to the ecosystem can result. Sufficiently long periods of drought can turn grassland into desert.

All organisms are acted upon by the environment in which they live and they, in turn, change the environment. Man occupies a position in the environment and necessarily interacts with it as well as with the thousands of other species of animals, plants, and microorganisms with which he shares the environment and upon whose metabolism he is dependent. Man's special place in the environment is a result of his unprecedented power to alter it and thereby either to increase the productivity of, or to drastically degrade his ecosystems.

That man's activities can cause ecological destruction on a large scale is well documented; e.g., the conversion of the once-fertile Tigris and Euphrates Valleys to desert through erosion and salt accumulation resulting from deforestation, faulty irrigation practices and the ravages of warfare. The increasing southern extension of the Sahara has been suggested to be a result of changing weather patterns caused by overgrazing and the resulting changed local albedo. As a hunter, man is thought to be responsible for the widespread extinction of a great number of indigenous large North American mammals. It is inaccurate to believe that the effect of man's activities on the physical and chemical parameters of the environment is negligible as compared to the natural flows of energy and materials.

NASA's interest in the area of ecosystem dynamics should center about the probability that the Agency may engage in activities that have a potential for affecting the global environment in ways sufficient to produce a measurable change in one or more significant ecosystems. The space shuttle program may have that potential. Clearly, accurate prediction of the qualitative and quantitative environmental effects of a NASA program will be increasingly necessary to any decision to undertake or modify the program. The question

then arises as to what options are currently or potentially available for predicting the effects of changes in the global environment on ecosystems.

A cursory examination of available options suggests that computer simulation of ecosystem dynamics as developed from mathematical modeling may be the most productive approach.

The use of simulation techniques in the analysis of a system is based upon the following considerations and limitations:

1. The real system is too complicated to understand in its entirety, or too sensitive to attempts to interact with it. Thus, we are forced to work with simplified substitutes for a real system. Such a system is chosen to illuminate a complete natural system or to be simple enough so that the whole system can be understood at some defined level.

2. Both the risks and the costs of failure in experimenting with the real system are high enough that we cannot work with a real system.

3. A real system is too expensive to duplicate, or too slow to react, or too inaccessible to work with.

In all of these cases, our only alternative is to substitute some form of simulation for a real system.

A consideration of the magnitude and complexity of global ecosystems suggests that all of the above conditions hold, and thus a simulation approach might be most profitable. One basic approach to simulations of real systems is to construct a mathematical representation of the system in a form which is useful for manipulation on an analog or digital computer. The model should illuminate some part of the real system, be consistent with available observations and, if the model is well chosen, allow correct predictions of observations that are yet to be made. One general goal of an ecosystem model might be to extrapolate from observations and to predict what is likely to occur in some hypothetical situation. In much the same way as it is possible to simulate the control and flight of an airliner or a spacecraft, it would be possible to test out the effect of various alterations or perturbations on the ecosystem in anticipation of the actual alteration or perturbation.

Computer simulation of ecosystems, from simple predator-prey interactions, to complex biomes, has been an area of active research in the past decade and has yielded useful models in the areas of resource management, environmental pollution and ecosystem dynamics (ref. 9). Many global ecosystems which would be affected by atmospheric perturbation (plankton, agricultural areas, conifer and deciduous forests, tundra and grassland) have been subjected to extensive modeling as part of the International Biological Program (ref. 10).

It must be emphasized that no model is a total representation of the real system, complete in all details. Ecosystems particularly have a

complexity and number of interactions which defy attempts at anything more than partial, highly simplified modeling. Yet these models can accurately represent the relevant interactions in a real system and in a manner useful for analytical and predictive purposes. Any real system can be looked at from many points of view; each one gives a different perspective of the system. Each view is valid inasmuch as it gives accurate information about the system and a collection of views, while not equal to the real system, permits a system concept to be formed.

The fact that each model represents a point of view of a real system suggests that not all models are equally useful to all investigators of a real system. Thus, the interest that NASA might have in a specific perturbation or a particular ecosystem (e.g., the effect of the continued injection of rocket exhaust-derived aluminum oxide microspheres into the atmosphere on cloud cover) may require a model different from available models. This reflects a difference in the specific concerns of NASA and of other modelers. This is an important point. A model must be developed to reflect the interests of the user of the model. This suggests that NASA must have the capability of developing or adapting models of ecosystem dynamics directly related to NASA and incorporating those environmental concerns and activities which are specific to the agency. NASA should not assume that appropriate models will be available at some future time when the need for a particular ecosystem model might be critical.

#### Approach to Problem

It is suggested that a productive initial approach to an examination of the feasibility of using computer simulation for the purpose of predicting the biological effect of an increase in UV-B flux would include:

1. Establishing contact with the several groups involved with constructing mathematical models of appropriate ecosystems and obtaining from them programs, sample data and printouts.

Several models of major ecosystems have been developed and are in the continuous process of updating and verification. Among them are models of eastern deciduous forest, lake, grassland, desert, conifer forest, and tundra.

2. Modifying such programs to include best estimates for the effects of increased ultra-violet flux on the components of the ecosystem.

3. Running such modified models to determine the effects of such increased UV flux on the various components of the ecosystem as well as on such parameters as total productivity.

4. Values for the necessary numerical constants and variables should be obtained from the literature where possible, and when not available, best-guess estimates should be used.

5. Methods and approaches for the experimental validation of the results of the modified models should be considered if so warranted.

6. Active interaction with such groups as the Atmosphere Modeling Group of the Theoretical Studies Branch at Ames Research Center and the Systems Ecology Group of the Environmental Sciences Division of the Oak Ridge National Laboratory currently in existence should be continued.

#### EPILOGUE

NASA programs have heretofore had a negligible effect upon the global environment. Present awareness of the potentially deleterious effect of space shuttle exhaust on atmospheric ozone, however, emphasizes both the possibilities for inadvertent modification of the atmosphere by future NASA programs and the inadequacy of present techniques for accurately predicting the resulting qualitative and quantitative changes in global environments and ecosystems. There are a number of NASA programs, both extant or proposed, whose effect on the global environment must be considered. Space shuttle, atmospheric microwave transmission and Mars surface sample return all have the potential of initiating a chain of events which could, to a greater or lesser extent, perturb global ecosystems. More importantly, it is likely that the problems generated by ever increasing human populations, shrinking reserves of nonrenewable resources, and an increasingly more complex and powerful technology, will become more critical. As a consequence, political stimuli to find solutions to these problems will increase, and the solutions themselves will become increasingly drastic. It is probable that NASA will become increasingly more involved in seeking technological solutions to global problems, and thus increasingly more involved in programs having a potential for impacting on the global environment.

It would seem necessary, therefore, that NASA consider an *organizational response* to the problem of predicting the biological effects of small, long-term perturbations in the global environment which might be caused by NASA activities. Because of the magnitude and difficulty of this problem, prudence suggests the immediate initiation of a study of this response rather than in a period when the threat of significant environmental perturbation is actual rather than potential.

Specifically, it is proposed that a study be undertaken to seek and identify the most promising approaches to the problem of predicting the qualitative and quantitative behavior of global ecosystems by examining the current programs of university and government groups in ecosystem modeling and simulation and determining the utility of this approach as a predictive tool.

It is suggested that an efficient and effective initial approach would be the organization or one or more informal discussion groups to consider these and related questions, and that a report of suggestions be prepared.

It should be emphasized that this initial phase will be primarily concerned with discussion, consultation, and idea exploration aimed at the development of a reasonable long-range strategy for dealing with the problem of predicting and evaluating the biological effect of ecosystem perturbation.

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