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Authors
Cicerone, Ralph J
Elliott, Scott
Turco, Richard P

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Ralph J. Cicerone, Scott Elliott and Richard P. Turco

All the signs are that global ozone depletion is increasing. Ideas to mitigate the problem that at first glance may seem far-fetched deserve more serious consideration and a scientific process of evaluation.

THERE is new evidence of a serious problem in the stratospheric ozone layer. Direct and immediate biological damage due to increased ultraviolet light in Antarctic waters has now been reported[1] and ozone in Arctic and northern mid-latitude regions may be threatened — even as international agreements (the Montreal Protocol), national plans and those of industries are being implemented and accelerated to stop the flow of chlorofluorocarbons into the atmosphere. It may become necessary to develop more aggressive strategies if damage from reduced ozone becomes intolerable. Should these include gross manipulation of the environment?

Many ideas about global environmental engineering have been casual, scientifically unsound, dangerous or all of these — for example suggestions such as exporting ozone to the stratosphere or 'sucking' chlorofluorocarbons out of the atmosphere. But serious suggestions are beginning to be made. Some interest arises from simple faith in technological fixes, some from technologists who wish to help, and some from large corporations with significant scientific and engineering capabilities in search of business opportunities. There are several major companies investigating possible projects, at least one of which has been granted a patent[2]. Ideas are also being raised by people concerned about environmental degradation.

By all measures, the Antarctic ozone hole is becoming a more serious problem. Average amounts of ozone measured each October have decreased sharply during the past 15 years; daily maximum and daily minimum amounts have also decreased; and the duration of these decreases has increased. Further, the area of reduced ozone has spread well into southern midlatitudes, possibly because of the export of ozone-poor air from the Antarctic stratosphere late each austral spring. Episodes of reduced stratospheric ozone over Australia have been recorded which suggest an Antarctic origin. Increased intensities of ultraviolet radiation have been measured beneath the hole, with intensities more typical of the summer occurring in early spring. Meanwhile, compelling experimental and theoretical evidence indicates that chlorine from chlorofluorocarbons is the main ozone-destroying agent and that the activity of chlorine is maximized by chemical reactions on the surfaces of polar stratospheric cloud particles. The fact that chlorofluorocarbons survive for about 100 years in the atmosphere implies that stratospheric chlorine will not return to pre-ozone hole values until late next century. Therefore, the Antarctic ozone hole will probably continue to develop each year, and the amount of ozone in the Southern Hemisphere will continue to decrease.

We are investigating a concept to close the ozone hole — the idea of injecting thousands of tons of alkanes (such as ethane or propane) into the polar stratosphere over Antarctica for about a month each year[3]. Alkanes (and their decomposition products) are relatively short-lived, so would not spread globally. There are many uncertainties underlying this idea, for example, information about the formation rates of polar stratospheric clouds and of chemical reactions on the cloud surfaces are badly needed. But we have attempted to evaluate key processes, to look for sensitivity to various assumptions and to look for possible side effects by means of a computer model. Our model shows that although ozone depletion could be prevented or slowed through annual alkane injections, there are other plausible outcomes in which small injections could worsen ozone depletion. It has now been proposed that there is a direct reaction of HCl and HOCl on the surfaces of polar stratospheric clouds[4]: this reaction could also alter the response to alkanes. So although our model is simplified, and serious questions of feasibility are not addressed, we suggest nonetheless that exercises like this are essential first steps in the responsible exploration of the feasibility of environmental engineering.

For an effective debate, publication of ideas in peer-reviewed journals and peer-review of research plans is essential. Detailed feasibility studies should wait until the underlying scientific concept is documented as well as reviewed critically and repeatedly. Analyses of engineering costs or of timetables for action are premature at this stage. Ideas for global environmental engineering are likely to be badly flawed technically, and will be seen to be so through review. Concepts that survive initial review must be refined and re-evaluated through independent studies, leading to useful revision or rejection. We hope that ideas will spur research as they expose weaknesses in our understanding of the Earth system, as seems to be occurring in the case of oceanic iron fertilization[5-7].

Social, ethical and legal questions will surround any serious proposal for global environmental engineering. Incomplete understanding almost always characterizes the behaviour of environmental systems; this is especially true of systems in which living organisms are central, as in the photic zone of the oceans[5-7]. Without understanding the mechanics of a natural system, there is little basis for predicting the system's response to perturbations. Accordingly, risks are inherent in any large-scale intervention — risks of unanticipated side-effects, of wasting time and resources, or of diverting attention from the root causes of environmental problems.

Who must make decisions and with what criteria? Are there any existing international laws that clearly forbid or regulate the treatment of the Antarctic stratosphere with alkanes or the southern oceans with iron? In any case, we believe that international, but non-governmental, bodies of scientists must be involved in the initial evaluations. Political judgements will also be required to express differing values and perceptions of risks — for example, those most threatened by inaction might press for intervention long before others would be receptive to such ideas.

We hope to stimulate debate and scientific research on these issues; their resolution will require serious, innovative thinking and extensive discussions. Their complexity could demand decades for significant progress. In the meantime we must address the underlying causes of environmental problems, if only to buy more time for us to understand the Earth as a system and the consequences of human interactions with it. □

Ralph J. Cicerone and Scott Elliot are in the Department of Geosciences, University of California, Irvine, California 92717; Richard P. Turco is in the Department of Atmospheric Sciences, University of California, Los Angeles, California 90024, USA.

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