G. Mégie, *Science and Engineering Ethics (2006)* ***12****, 596-606*

From Stratospheric Ozone to Climate Change: Historical Perspective on Precaution and Scientific Responsibility*

Gérard Mégie *(1946-2004)*
Founder, Institut Pierre Simon Laplace, President, CNRS (2000-2004)
Université Pierre et Marie Curie

Keywords: stratospheric ozone, impact of human activities, CFCs, Montreal Protocol, historical case study, scientific uncertainties, Precautionary Principle, Precautionary scenario, cost-benefit analysis, regulation

ABSTRACT: *The issue of the impact of human activities on the stratospheric ozone layer emerged in the early 1970s. But international regulations to mitigate the most serious effects were not adopted until the mid-1980s. This case holds lessons for addressing more complex environmental problems. Concepts that should inform discussion include 'latency,' 'counter-factual scenario based on the Precautionary Principle,' 'inter-generational burden sharing,' and 'estimating global costs under factual and counter-factual regulatory scenarios.' Stringent regulations were adopted when large scientific uncertainty existed, and the environmental problem would have been prevented or more rapidly mitigated, at relatively modest incremental price, but for a time delay before more rigorous Precautionary measures were implemented. Will history repeat itself in the case of climate change?*

I. Introduction

The issue of the impact of human activities on the stratospheric ozone layer was first raised in the early 1970s. At that time, the emission of nitrogen oxides by supersonic aircraft was suspected of inducing a possible reduction in the ozone layer which protects the planet from harmful solar ultraviolet radiation. The perceived threat of nitrogen oxides, which several years later turned out to be scientifically unfounded, was enhanced in 1974 when Sherwood Rowland and Mario Molina identified

* An earlier version of this paper was presented at a conference on "Issues of Risk and Responsibility in Contemporary Engineering and Science: French and U.S. Perspectives," organized by the France-Stanford Center for Interdisciplinary Studies and held at Stanford University, April 7-8, 2003.

Address for correspondence: Robert McGinn, Stanford University, Science, Technology & Society Program, Bldg. 370, Rm. 110, Stanford CA 94305-2120, USA; email: mcginn@stanford.edu.

Paper received, 10 April 2004: accepted, 31 August 2006.

halogenated hydrocarbons (chlorofluorocarbons [CFC] and bromofluorocarbons or halons) as sources of chemically active chlorine and bromine in the stratosphere which could in turn destroy the ozone layer(1). The results of more than three decades of research have provided a progressively better understanding of the impact of human activities on the chemistry and physics of the global stratosphere. This effort in environmental research has been conducted in the framework of international programmes such as the International Geosphere Biosphere Programme and the World Climate Research Programme. It has led to new policy-relevant insights into the role of trace constituents emitted into the atmosphere by human activities. These insights have been given to decision makers in the frame of various conventions and organisations. These include: (i) the 1985 Vienna Convention and 1987 Montreal Protocol on ozone-depleting substances and its subsequent Amendments and Adjustments; (ii) the International Civil Aviation Organisation (ICAO) which is responsible for regulation, including environmental, of international air traffic, and (iii) the 1997 Kyoto Protocol on substances that alter the radiative forcing[a] of the climate system.

These political decisions have been based on atmospheric observation and model studies which showed long term declines in stratospheric ozone at both mid- and high latitudes. The most dramatic manifestation of such a destruction of the ozone layer is the "Antarctic ozone hole" which appears each austral spring over the South Pole. This phenomenon corresponds to the first non-linear effect in the global environment which can be directly attributed to man-made influence. This means that the increase in chlorine and bromine loading in the stratosphere due to the emissions of CFC and halons has reached a level where non-linear processes which were negligible in the pre-industrial stratosphere, suddenly became the dominant ones. The analogous ozone depletion in the Arctic regions was not as severe, although substantial late winter/spring ozone destruction was observed during unusually cold stratospheric winters in the 1990's. However, although less severe, this diminution affects areas of the globe which are heavily populated, and thus corresponds to a higher risk in terms of human health.

Indeed, the impact on human health which has driven politically the stratospheric ozone issue is related to the fact that solar ultraviolet radiation has an important influence on human beings and on ecosystems, and that the ultraviolet intensity at the ground is directly influenced by the total column of ozone. However, the problem is further complicated by the fact that other factors, including cloud cover, solar elevation, atmospheric aerosol, altitude and local albedo,[b] also influence solar radiation at the ground. It is clear that when these factors do not change, an ozone reduction results in an increase in B-type ultraviolet (UV-B) radiation. However, there is no observational proof that UV radiation has increased in areas of the globe other than the

---

a. "Radiative forcing" is any change in the radiation (heat) entering or leaving the climate system. (From Wikipedia, http://en.wikipedia.org/wiki/Radiative_forcing)

b. 'Albedo' is a ratio of scattered to incident electromagnetic radiation power, most commonly light. It is a unitless measure of a surface or body's reflectivity. The word is derived from *albus*, a Latin word for 'white'. » (From Wikipedia, http ://en.wikipedia.org/wiki/Albedo)

Polar Regions, where the ozone destruction is sufficiently large to be the dominant process.

As of 2003, the chlorine content in the stratosphere appears to have reached its maximum level and should now start to decrease in response to the enforcement of the Montreal Protocol and its amendments. Although the stratosphere still remains a region of major concern for both climate impact and the surface environment, and although the complete recovery of the ozone layer could not be expected before the middle of this century, one could try to draw a few lessons from what might be considered as the history of the first global environmental problem for which regulatory measures have been decided and enforced at the international level. Such an analysis can be made in terms of application of precaution, scientific uncertainties, and time constants related to both the environmental evolution and the political decision process. It can also lead to "rewriting" the history to identify what would have been a more efficient path which could have led to a reduced impact on the Earth's environment.

II. Historical Perspective

Organo-halogenated compounds (CFCs and halons) were synthesized for the first time in the 1930s and put efficiently on the market after the Second World War. The application of the Precautionary Principle[c] (see below) at that time was quite impossible because the processes which govern the natural balance of ozone in the stratosphere were not fully identified and quantified until the end of the 1960s. In 1986, the worldwide production of CFCs and halons, including the two most abundantly produced species identified hereafter as CFC 11 and CFC 12, reached about 1.5 million tons. This figure includes the production officially recorded by Western countries, and a more approximate value of the production of Eastern countries and China. These compounds were then emitted into the atmosphere with a variable delay, depending of course on their use. In the case of aerosol sprays, they were being emitted immediately, whereas for refrigeration uses, it could take several years. The CFC used in the production of insulation foams is trapped within the closed cells of the rigid foam, so its release can occur decades after production if it is used in furniture or building materials. There is also a several-years-long latency between the production and the release of halons which are used in fire suppression systems with a typical shelf life of twenty years.

In addition to this period of latency, a second time period of 3 to 5 years on average is necessary for CFCs to reach the stratosphere and be photo-dissociated by solar radiation. Therefore, from the production of these gases to their negative consequences on stratospheric ozone, an average delay of ten years has occurred. As

c. There are many formulations of the Precautionary Principle. Principle 15 of the Rio Declaration (adopted at the 1992 Rio Conference on the Environment and Development) states that "in order to protect the environment, the precautionary approach shall be widely applied by States according to their capability. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."[2 (p. 11)] such, the state of the ozone destruction cycle in 1998 was mostly determined by CFC emitted before the end of the 1980s, that is before regulations were developed. This is why chlorine content in the stratosphere continued to increase after CFC production had been virtually stopped in 1995-1997, and why the relative concentration of stratospheric chlorine reached its maximum value around 2000-2001.

This inertia linked to atmospheric time constants has two effects:

- first, early observations of evolutive trends in the mid-1980s only included CFC emissions prior to 1970. This is less than 25 percent of the total historical emissions by that date. Between 1950 and 1986, CFC production had increased by 6 to 10 percent per year, on average. In other words, the observed impact is a relatively small fraction of the impact yet to come but already committed to. The destructive effects of CFC emissions have been unknown for a rather long time.
- second, once regulations have been implemented, their positive impacts can only be measured after a decade. Meanwhile, one can only record a change in trends. The return to equilibrium will be much longer, for it depends on the lifetime of the different CFCs, which varies from several decades to several centuries, depending on the specific compound being considered.

The consequence of the fast emission growth is that the stratospheric chlorine content has been multiplied by almost a factor of seven, from 0.55 parts per billion (ppb)—the pre-industrial value linked to methyl chloride emissions by the oceans—to 3.8 ppb in 1995. The maximum level was probably reached in 2000 and one will have to wait until 2050 to observe a return to values lower than 2 ppb. This level, which was reached for the first time in the stratosphere in 1980, is considered critical because it corresponds to the first observation of large ozone destruction in the Polar regions correlated with heterogeneous chemical processes (the Antarctic ozone hole).

Current quantitative understanding of the mechanisms which govern the behavior of stratospheric ozone is based on sophisticated numerical models that simulate well the chemical and physical reactions in the atmosphere. From such models, it is possible to calculate rather precisely the maximum amount of organic chlorine that the stratosphere is able to assimilate each year, if we want the chlorine loading to remain below the critical 2 ppbv [parts per billion by volume] ceiling. This quantity corresponds to 200,000 tons of chlorine emitted in the form of CFC, which corresponds only to 20 percent of the maximum emissions of 1986 and 1987. When the Montreal Protocol was first signed in 1987, the total production of CFC was 1 million tons. Thus, this production would have to be reduced by a factor of 5 in order to stabilize the stratospheric chlorine content. The Montreal Protocol could thus be considered half a solution, since it recommended reduction of CFC emissions by only 50 percent. Its sole consequence was to slow down the growth of stratospheric chlorine concentration. Because of these quantitative considerations, the return to equilibrium clearly would require totally stopping CFC emissions, at the shortest notice. This decision was taken in Copenhagen in 1992.

Since the 200,000 ton level was first exceeded before 1970, another element must be mentioned. Assuming a constant emission level of 1 million tons per year, each extra year of CFC production introduces into the atmosphere 5 times more chlorine than what could be eliminated in the stratosphere. If no decision is taken, 5 extra years will actually be necessary to return to values corresponding to the pre-industrial equilibrium. The moral of this story is that a 50-year atmospheric imbalance has resulted from 10 years of indecision.

III. A Counter-factual Precautionary Scenario to Evaluate Time Constants

In 1978, the worldwide production of organo-halogenated compounds was 800,000 tons, four times the limit level. The stratospheric chlorine load is 1.2 ppb, twice the value of the pre-industrial era, but still much below the level when phenomena linked to heterogeneous chemical processes appear. In the United States of America, the first assessments of the state of the ozone layer were published by the National Academy of Science. They were rather alarmist regarding the reduction of the ozone layer, but rather moderate with regard to the potential consequences on human health and on the biosphere. Nevertheless, several countries decided to propose a reduction in CFC use in aerosol sprays. At that time, these uses represented almost 50 percent of U.S. production.

Assuming that a strong application of the Precautionary Principle would have prompted an international proposal for an immediate effective reduction on the order of 50 percent, not of the consumption of CFC but of its production, then production would have stabilised at 400,000 tons per year for the following years, before further confirmation of the potential risks of deterioration of the ozone layer. Such a regulation would not have stopped the growth in the stratospheric chlorine content, since annual emissions would still be way over the sustainable sink capacity consistent with the critical 2 ppbv ceiling. Indeed, even if CFC production remained limited to 400,000 tons forever, the equilibrium level which would be reached within decades would still be high at about 9 ppb.

But the first round of abatement would have immediately and largely reduced the rate of growth of the chlorine content, so that a year of no-decision before the implementation of more drastic regulations would have resulted in only one extra year before equilibrium reappeared. This reduction in growth would have allowed, for example, the relative concentration of total chlorine content in the stratosphere to have reached about 2 ppb in 1988, rather than in 1980. Because regulatory measures were not in place until 1978, they did not impact the stratosphere before the mid-1980s. One can thus assume that the effects observed before 1985 were the same as in the real world, so that the first reliable measurements of the global ozone trends (which prove that the ozone concentration has actually decreased by 5 percent between 35 and 45 km in altitude) would still be reliable. Although the total ozone content is only moderately affected, one can assume that these data are sufficient to implement new regulations at the international level.

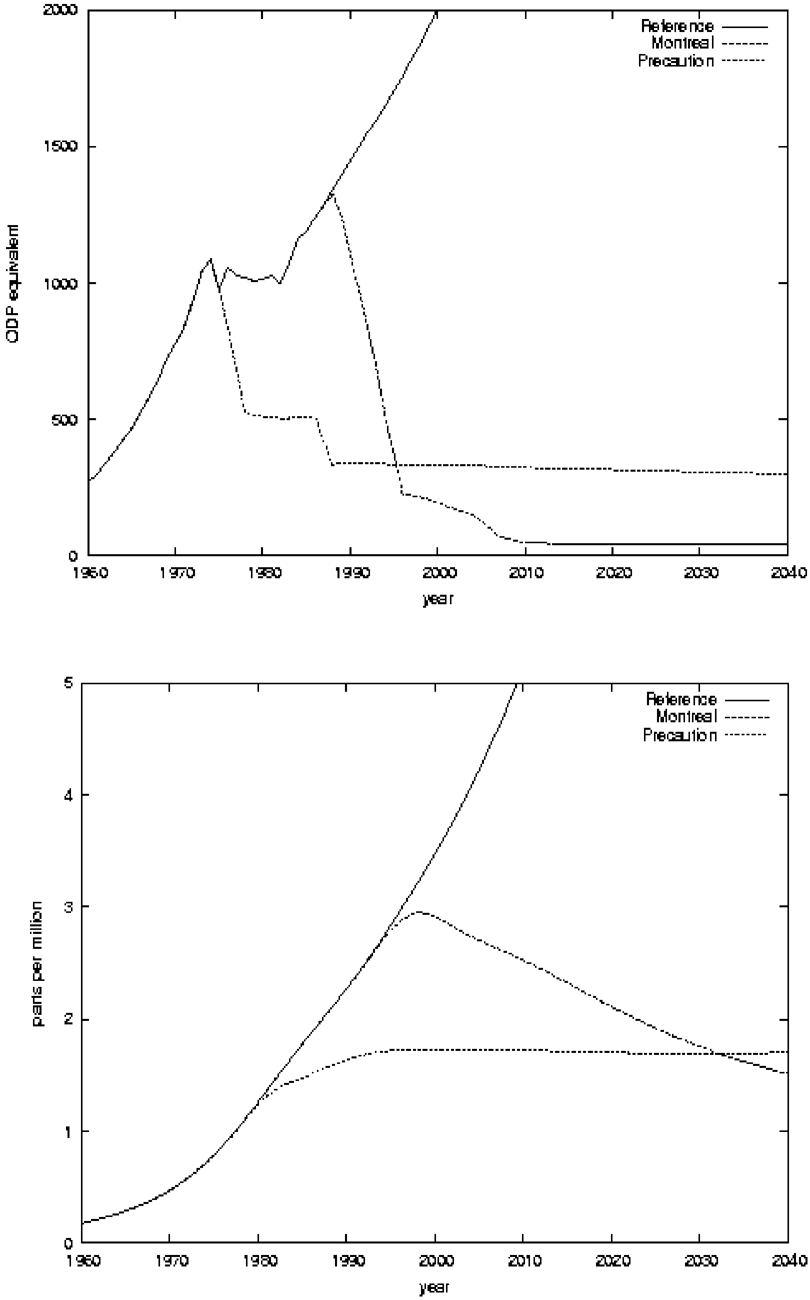

Figure 1. *Consumption (top panel) and equivalent chlorine loading in the stratosphere (bottom panel) for three scenarios: reference scenario (no protocol), realised scenario in reference to the Montreal Protocol, counter-factual scenario.*

This could correspond to a further 50 percent reduction in CFC production. This possibility is reinforced by the fact that substitution products, which enable replacement of CFCs for their main uses (refrigeration, foams, solvents), are available.

This is a conservative assumption since in the counter-factual scenario employing the Precautionary Principle, earlier and stronger regulations would have hastened rather than retarded the development of alternatives. The yearly maximum emission is now limited to 200,000 tons. Finally, a slight reduction at the turn of the millennium enables one to compensate for the impact of the substitutes—the hydro-chlorofluorocarbons HCFCs which contain chlorine)—whose effect on ozone, because of their shorter lifetime, is much less than that of the CFCs.

With this hypothetical scenario, two distinct actions within a decade would have allowed the stratospheric system to restabilise as soon as the early 1990s, with the stratospheric chlorine content at about 1.9 ppb. The plausibility of this counter-factual scenario hinges on two critical assumptions: 1) that indeed 200,000 tons per year is an acceptable limit for global emissions of organo-halogenated compounds, an assumption that seems plausible using up-to-date simulation models of the stratosphere; and 2) that the cost of this counter-factual scenario is not inordinately large compared to what actually happened, as presented in the next section.

IV. Precautionary Principle and Cost-Benefit Analysis

To simulate the consequences of the counter-factual scenario, an integrated assessment model was built which couples a chemistry-transport model of the stratosphere with an economic model. (See Figure 2, overleaf)[d] The solid line shows the actual Montreal scenario cost curve. The initial plateau corresponds to $500 million per year spent between 1974 and 1978 to develop CFC substitutes. The subsequent gap between 1979 and 1986 corresponds to the period of scientific controversies before the ratification of the Montreal Protocol. During this period there was significant change in the mix of CFC uses. But the cost curve is set at zero logically because this is a model of the costs of the Montreal protocol.

Consider now the incremental cost of the more precautionary scenario. Comparatively, it costs about $2 billion more annually during the first two decades. Then the costs are about the same during the next fifteen years. However, it brings a benefit of about $1 billion per year after 2010. This benefit arises from the fact that ozone-depleting substances are not completely banned from the industry, but can still be used for essential purposes almost indefinitely.

This shows that comparing the two scenarios is essentially a question of intergenerational burden-sharing. There is no universally accepted way to compare the two streams of expenses over such a long time period. Therefore, one could stop here and conclude by saying that the two cost curves are essentially of the same order of magnitude. Early action costs more up-front but saves some further down the road. The biggest benefits of early action would have been to avoid the ozone hole, but these benefits are not quantified in monetary units here.

---

d. These models and the methodology used for the economic calculations have been extensively described by M. Ha-Duong, G. Mégie and D. Hauglustaine.[3]

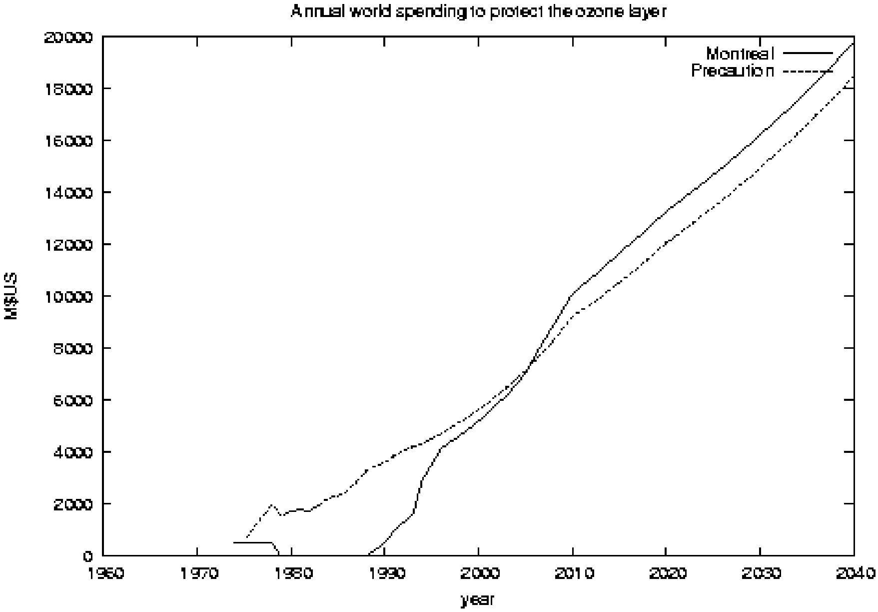

Figure 2. *Global spending to replace ozone depleting substances emissions. The cost of substitution (M$) is aggregated over fourteen relevant techno-economic sectors. For each sector, the cost is the product of the quantity of chemical compounds used by the incremental substitution cost.*

However, to present the results at a more detailed level, it is necessary to aggregate the temporal dimension by using inter-temporal discounting. All cost profiles are calculated in 1997 US dollars at a 5 percent rate, summing from 1975 to 2075. The total figures are thus highly sensitive to the discount rate, and the results have thus to be explored cautiously and comparatively. The total cost to the world under the Montreal scenario is about $256 billion. But, as already indicated, changing the discount rate by two points up or down changes the total substitution cost by about 80 percent. It appears that this global cost is about 13 percent higher under the Precautionary scenario. In addition, a lower discount rate, or a longer time horizon, implies a smaller difference in relative costs. For example, at a 2 percent discount rate, the difference was about 3 percent, not 13 percent. A zero discount rate with a sufficiently long time horizon would certainly imply a cost advantage for the counter-factual scenario. In all cases, this suggests that the additional costs of earlier action would have been modest, around 10 percent of the total cost of action.

V. Conclusion and Lessons

The protection of the ozone layer is admittedly a success, as ozone depletion levels are observed to be stabilising now. Yet the environmental policy community should strive to achieve even greater successes in the global atmospheric challenges now in front of us. This paper has argued that greater success would have been possible, by showing that a scenario completely avoiding the hole in the ozone layer was feasible at small additional cost. Indeed, in the mid-seventies early warnings led to a decade-long pause in the growth of emissions of ozone depleting substances. Had they instead led to a significant reduction in emissions, the hole could have been avoided. Moreover, significant essential use of CFCs and other substances could have been extended forever. This hypothetical scenario shows that two distinct actions within a decade could have restabilized the stratospheric system by now.

Results of the economic analysis show that the Precautionary scenario costs about two billion dollars more per year during the first two decades. However, early action would have saved about one billion dollars a year after 2010 because it would have allowed for continued use forever of ozone-depleting substances for essential uses. Admittedly, if the level of atmospheric chlorine had been controlled to remain under 2ppb, then scientists would not have discovered the importance of heterogeneous chemical processes. They would still be convinced that the processes discovered in the 1960s are sufficient to explain the balance of the stratospheric ozone layer. The ecological disaster of the Antarctic ozone hole would not have occurred and it might have been more difficult to convince pseudo-experts and sceptics of the merits of the second round of regulations.

This raises the question of whether the ozone hole was necessary to spur the global community into more stringent CFC controls. Although this political science question cannot be answered definitively, it is fundamental to understanding the essence of the Precautionary Principle. In reality, sceptics were not convinced before the disaster. Yet not only was the impact of inaction underestimated, but the anticipated costs of controls were considerably overestimated. Indeed, the dynamics of technological change forced by the United Nations Environment Program's (UNEP) Technology and Economic Assessment Panel allowed control of emissions at a lower cost than initially thought. Therefore, costs were overestimated and benefits underestimated. With perfect foresight, the cost-benefit analysis implicit in all policy decisions would probably have indicated that the early action scenario was superior. This is because it does not cost much more, and the benefits of avoiding the ozone hole are presumably large. However, with the limited information available at the time, not following the Precautionary trajectory might have been a rational choice. Yet, the early action scenario could also have been a rational choice. Is not this the essence of the Precautionary Principle?

Therefore, the conclusion is probably that the Montreal Protocol was only a partially successful application of precaution, due to the time delay before a decision was taken. But one can also draw a few lessons from this history of stratospheric ozone depletion, lessons that are probably valid for other environmental problems:

1. scientists strive to understand systems which continuously evolve under man-made forcing. Nevertheless, since in such cases uncertainties dominate, a better scientific knowledge of the Earth's system does not immediately result in reduction of those uncertainties;

2. due to these uncertainties in system behaviour, one cannot rely on "engineering of the environment" to solve the problem;
3. the response of the environmental system could be non-linear, thus linear extrapolation can give a less dramatic view of the future than what will really occur;
4. the time delay for a no-regret decision is not infinite, and the time constants involved in the Earth's system have to be considered carefully;
5. when there is not much information, that is, under large uncertainty, the different courses of action cannot always be compared by balancing the costs and the benefits; and, finally,
6. in the case of stratospheric ozone, the more stringent regulations were adopted at a time (1987) when the largest scientific uncertainty existed, since quantitative understanding of the ozone hole processes had not been fully realized.

In addressing other environmental matters, in particular the climate change issue, one can already be worried that no regulatory measures have been taken at the international level. Also, one has to keep in mind that the ozone problem was much simpler in terms of an economic decision because substitutes already existed, and because worldwide production of organo-halogenated compounds was strongly concentrated in particular locales.

In the case of climate change, similar questions arise with regard to understanding the Earth's system, possible impacts, and technological and societal solutions (mainly related to energy production). Indeed, numerous uncertainties still characterise the current understanding of the Earth's system and our capacity to predict the future evolution of the climate on Earth. These uncertainties also directly impact the identification and quantification of the different kinds of risks to be faced in the present century. Several questions thus remain, the most important one being the challenges raised by the fact that human-induced changes in the environment add to problems already posed by poverty, disease, and malnutrition which plague a large part of humankind. Some societies will probably adapt to such changes, but others, probably a majority, will not be able to do so due to their present state of development. What answers can be given to them when the modes of economic growth in the developed countries are not compatible with the requirements of global sustainability? While facing this complexity and this change in the relationship between humankind and nature, how can relevant research strategies be defined?

When considering the energy issue, an additional set of questions arises. What will be the future energy use by developed and developing societies? How much energy will be needed? What problems will occur and what research is needed to solve these problems? These fundamental questions will have to be quantified and put into context with other societal needs to develop scenarios concerning how best to balance economic growth, social development, and environmental protection. It is also expected that the proposed approach would necessitate and encourage closer collaboration among researchers from different disciplines as well as dialogues between various stakeholders in the society.

From this analysis, it is clear that the importance and difficulty of these fundamental questions differ by at least a few orders of magnitude from those related to the ozone problem. Nevertheless the central/primary question remains: will it be possible to regulate global atmospheric environmental issues before surprising non-linearities occur? Put differently, will regulation be possible before the catastrophic effects of human impact on the environment begin to occur?

REFERENCES

1. Molina, M. J. and Rowland, F. S. (1974) "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone," *Nature*, **249**, 810-812, 28 June 1974.
2. Commission of the European Communities (2000) "Communication from the Commission on the Precautionary Principle," February 2, 2000, p. 11.
3. Ha-Duong, M., Mégie, G., and Hauglustaine, D. (2003) "A Pro-Active Stratospheric Ozone Protection Scenario," *Global Environmental Change-Human and Policy Dimensions*, **13**(1): 43-49.