Apocalypse Soon?
Wagering on Warnings of Global Catastrophe

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Four Models of Global Systems

Scientists have turned their attentions to computer modelling as a method for studying global systems in order to evaluate claims of potential catastrophe and to see whether intervention is possible. In chapter 2, I will discuss the nature of modelling in general. In this chapter, I will sketch some well-known models of global systems designed in response to fears of global catastrophe and supply some of their history.

The models I am interested in each deal with a unique problem. These models of global systems examine the potential of some human activities to result in catastrophe. Nuclear winter, ozone depletion, overpopulation, and global warming are potential catastrophes brought about by human behaviour that are global in scope and have potentially irreversible consequences. Unlike models of local systems, these global models cannot be fine-tuned by trial and error. We cannot perform experiments on global systems to see whether the predictions made by models of nuclear winter are accurate. The unique nature of the dilemma is that we need to decide whether to act to prevent these potential catastrophes before we have strong evidence whether our fears of them are even realistic. Scientists hope that the results of the modelling exercise can be used by policy-makers to guide human action.

NUCLEAR WINTER

If the direct catastrophic consequences of a nuclear war were not bad enough, various scientists were warning in the early 1980s of the possibility of a new and previously unimagined disaster: nuclear winter. While the radioactive fallout and breakdown of organized society resulting from a nuclear war would certainly be horrific, the end of all life on the planet was not usually included among the consequences.[1] However, the ensuing global climatic effects might indeed ensure the apocalypse. Computer modellers conjectured that in the aftermath of a nuclear exchange, such a large quantity of soot and dust particles would be dispersed throughout the atmosphere that they might change the climate. The dust cloud might reflect so much sunlight back into space for such a long period of time that Earth would be plunged into a winter that would have catastrophic effects on the planet's life. Thus, it was urged that the global nuclear stockpile be reduced to a level below that which would trigger this potential catastrophe.

One of the first, and certainly the most influential, of the nuclear winter models was published in 1983.[2] Its simplicity was part of its persuasive force. The calculations were based on a representation of the atmosphere as a $1\ \text{cm}^2$ column of air, and the only variables considered were the area, the quantity of fuel in that area, and the amount of smoke that would be produced by burning. The authors claimed that the model was partially inspired by an analogy with volcanic eruptions and Martian dust storms. Study of these phenomena revealed that there are two simple mechanisms by which dust, soot, and sulphuric acid aerosols cool global temperature. First, these particles directly lower the global temperature by reflecting sunlight and thus reducing the amount that reaches Earth's surface. Second, they indirectly cause cooling by acting as condensation nuclei in cloud formation, thus further blocking sunlight. This simple model ignores regional geography; the effects of the wind in transporting the smoke around the globe; the heat capacity of the oceans; the effect of possible coagulation of particles; the altitude of the smoke cover, as well as whether it was a continuous blanket or in patches; and other complicating details. It is nevertheless able to explore the basic mechanisms behind the temperature changes expected from different amounts of particles blocking sunlight.[3]

Other models followed from researchers around the world. Unfortunately, the range of these predictions was far from precise. Tony Rothman reports that one model showed a potential attenuation factor of sunlight in the range of 2 to 150 times, while other models predicted temperature drops of 35, 20, and 8°C.[4] Nonetheless, each of these modellers regarded the others as confirming their own findings.

Besides lack of precision, there were many other problems with the models. Many of the predicted effects were based on an analogy with the behaviour of the sulphuric acid aerosols released in volcanic eruptions – but these would not be present in the nuclear winter case and there was no evidence to support the assumption that soot and dust would behave in the same way as the sulphuric aerosols.[5] In the USSR Academy of Sciences model of Aleksandrov and Stenchikov, no distinction was made between dust and soot with respect to their different reflective properties; this resulted in an overestimation of the nuclear winter effect.[6] There were large uncertainties with regard to the quantity and "blackness" of smoke that would be produced, as well as how much would be immediately washed out by rain (estimates ranged from 10 to 80 percent).[7] There was disagreement over whether there was a minimum threshold level implying that a relatively small burn area would trigger the full nuclear winter effect. (This concept was central in arms policy considerations with regard to desirable levels of total world stockpiles and the advisability of limited strikes.)

Despite their problems, nuclear winter models gained a great deal of support. The rapid acceptance of the nuclear winter vision might have been a result of its powerful imagery, which gripped anyone who heard it in a poetic, but nightmarish daydream. However, in his essay "A Memoir of Nuclear Winter," Rothman argues from personal experiences and discussions with some major participants that this widespread acceptance of a suspect model was a result of the noncritical stance that most scientists adopted for political reasons. (I will discuss these sorts of reasons for accepting predictions of global catastrophe in part 2.)

Later, more complicated models were designed, and the conclusions had to be modified to allow for the mitigating effects mentioned above. It turned out that the nuclear winter models were not "robust"; that is, small changes in the initial conditions and assumptions would result in wide variations in the predictions of temperature decreases and duration of the dust cloud. Since estimates of the amount of smoke produced by nuclear explosions are very uncertain,[8] this sensitivity of the model to small changes in assumptions is a serious defect. For example, if the nuclear exchange takes place in the winter season instead of the summer season, the temperature drop is smaller by one order of magnitude.[9]

S.L. Thompson and S.H. Schneider argue that, as a result of the above considerations, the deep-freeze interpretation of nuclear winter is now dismissed by most scientists as unlikely. Instead, these authors suggest that we think in terms of a nuclear autumn rather than a nuclear winter.[10] While not suggesting that nuclear war will have no other lasting environmental effects, Thompson and Schneider nonetheless argue that "on scientific grounds the global apocalyptic conclusions of the initial nuclear winter hypothesis can now be relegated to a vanishingly low level of probability."[11] That is, there does not seem to be the potential for human extinction resulting solely from the climatic change that would follow nuclear explosions. The *possibility* of nuclear winter still exists, but the revised models suggest a much lower *probability* than the original models, as well as the absence of any minimum threshold.

OZONE LAYER DEPLETION

What is interesting about the history of models of ozone layer depletion is that the fear they generated was sufficient to initiate worldwide preventive action *before* any consensus was reached about the plausibility of the models and before there was any measurable damage.[12] In this case, the causal evidence was not discovered until afterward. Action was taken to reduce the use and release of CFCs (chlorofluorocarbons) as early as 1978. However, it was not until 1988 that a study of the Antarctic atmosphere was published that revealed that there was a direct correlation between increased concentrations of chlorine and decreases in ozone.[13]

The first publications that implied that CFCs might be damaging the ozone layer came in 1974.[14] CFCs migrate up to the stratosphere where they are broken down by short-wave ultraviolet radiation. As the CFCs break down, the chlorine released acts as a catalyst in an ozone destroying reaction that takes place on ice crystals created in large polar vortices. A single chlorine molecule can destroy about 100,000 molecules of ozone.[15] As the ozone thins, the amount of UV-B radiation reaching Earth's surface increases, and this results in an increased frequency of skin cancer and retinal burn, the suppression of immune systems, decreased agricultural yields, and even, perhaps, the death of the oceans, as UV-sensitive plankton and other creatures low on the food chain are destroyed.

The effective political actions of a strong environmental movement led to preventive action being taken as early as 1978, with a ban on aerosol sprays in the United States, Canada, Norway, and Sweden.[16] However, the production of CFCs for other uses (refrigeration, thermal insulation) continued to grow. It was not until 1984 that the ozone hole over Antarctica was first noticed. A 40 percent decrease in ozone over ten years had gone previously unnoticed because researchers had rejected low readings as anomalous.[17]

The nature of the phenomenon was yet to be understood. Explanations and evidence would not come until three years later. Nonetheless, international political agreements were reached in 1987 to limit production and use of CFCs. An international agreement to reduce CFC use, known as the Montreal Protocol, was signed in 1987. Soon after, the results of a crucial experiment were published. A NASA research plane had flown over the Antarctic taking measurements of the relevant variables. The measurements revealed that decreases in ozone concentration were directly proportional to concentrations of chlorine present.[18]

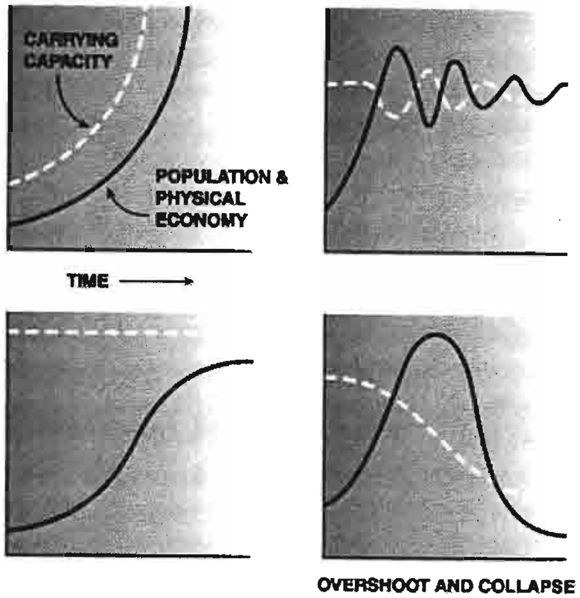
OVERPOPULATION

The population of Earth has just reached approximately six billion, and it is still growing. While it is clear that we must reflect on the potential consequences of our current rate of population growth, it is not obvious to everyone that the growth itself must soon end. On the one hand, there are those who believe that our resources are very limited and, therefore, that we must take preventive measures to limit growth now, or else expect the much less desirable checks of massive famine and global economic collapse. Others maintain that we have enormous supplies of cheap energy – the sun or the wind or uranium – and vast quantities of untapped metal resources on the ocean floor and in Earth's core. Even if these resources are ultimately limited, there is still room for a huge increase in population. We are often reminded in these arguments that, because the added population also contributes to production, an increase in population is not simply a drain on our finite stock of resources – the more the merrier, so to speak.[19] The point of this argument is that the globe's carrying capacity cannot be described as an absolute limit that is independent of other contexts. In the words of L. Sjoberg, "Carrying capacity is a socially organized threshold and not a simple technological phenomenon."[20]

One of the most influential arguments in support of the conclusion that we have exceeded, or will very soon exceed, Earth's carrying capacity is to be found in Meadows et al.'s *The Limits to Growth* (and later in Meadows et al.'s *Beyond The Limits*). The claims made there are based on a computer model of Earth that attempts to take into account the interactions of several systems. This "system dynamics" model characterizes the planet in terms of several components – population, pollution, resources, food production, and other interrelated subsystems. First it gives descriptions of the behaviour of each subsystem (for example, population grows exponentially in certain circumstances) and the connections between these component systems (for example, supply and demand laws, the effects of pollution on agricultural yields, delayed reactions, and any known positive and negative feedback loops). These descriptions are a mixture of theoretical assumptions and empirical measurements. The model then makes countless calculations in an attempt to discover the dynamics of the whole system under different initial conditions obtained by varying assumptions about such matters as resource availability or technological efficiency.

The authors identify four possible futures that would result under various assumptions.[21] The population and economy could (1) grow continuously, (2) slowly approach a limit and then stabilize, (3) overshoot the limit slightly and then oscillate above and below that limit in a series of minor crises and recoveries, or (4) overshoot the limit and "collapse" inelastically. The authors reached the conclusion that, if the world's systems continue to operate in the same manner as today, then the fourth future they describe will be our future – the world will overshoot its limits within one hundred years and collapse irreversibly.[22] Desertification, depletion of fisheries, loss of species, and losses in industrial capacity will be so sudden and severe that recovery, if it occurs at all, will take decades at least. (In fact, they claim we have already overshot limits in several areas.[23]) This catastrophic future will result because the indicators of problems are delayed (for example, it takes about fifteen years for CFCs to migrate to the stratosphere, where they start to break down ozone[24]), responses to these problems are often slow, and many subsystems are unable to recover quickly, if at all, after large setbacks.

The model is not specific about how global collapse will come about. It can come in various ways – depletion of natural resources or economic failures, for example. Unfortunately, if one of these paths to destruction is avoided, another one is precipitated. Diverting financial resources from polluting industries will, given one scenario, lead to economic collapse. So too will boosting agricultural production in order to feed a growing population. Thus, the model reveals that the problem is not simply one of physical limits to the world's finite natural resources but rather one of limits in what they call the world system's "ability to cope."[25] The writers are claiming that their model reveals that our future is threatened by population growth not simply because resources are scarce but also because of the inherent and inescapable problems arising from the structure and organization of our world system. Thus, the writers claim, even with very optimistic assumptions about increased economic and technical efficiency, recycling, improved agricultural yields, and pest control, the world system will still suffer a collapse under the weight of growing population.



Four modes of population approach to carrying capacity
Based on figure 4-2 in Meadows, Meadows, and Randers, *Beyond the Limits*.

GLOBAL WARMING

Recent climate models built to study the threat of global climate change imply that should present patterns of human behaviour persist and the concentration of carbon dioxide, methane, nitrous oxide (greenhouse gases) continue to increase over the next hundred years, the average global near-surface temperature will increase 1.4-5.8 °C. The Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean temperature will increase approximately 0.1- 0.2 °C per decade and before the year 2100 will be at least 3°C above current averages.[26] The stratosphere, meanwhile, will undergo a cooling effect. Sea levels might rise as a result of both thermal expansion of the water and increasing run off from melting ice caps. The interior of some continents will become more arid and the frequency and severity of hurricanes and typhoons could increase.[27]

Some observers argue that the average global mean temperature has already increased by 0.3–0.6°C over the last hundred years. If they are right, a plausible explanation for this increase is the action of the greenhouse gas warming effect represented in these models. On the other hand, the existence of a statistically significant increase is disputed,[28] and the increase is not outside the limits of natural variation anyway.[29] The climate cycles naturally on several different time scales as well as fluctuating randomly; for example, sunspot cycles and the El Niño effect are both major factors in determining global climate. There are also long-term balances and energy shifts between the various global components. The natural variability of Earth's climate is determined by changes in ocean circulation, atmospheric dust, and long-term fluctuations in Earth's "wobble" (Milankovich cycles) as well as changes in solar radiance. Because the temperature increases predicted by global climate models are, so far, too small to distinguish them as outside the natural limits, any evidence for such increases is incapable of confirming global warming theory. The influence on climate of natural system cycles continues to be much greater than that of human behaviour.

Even an absence of a measurable global warming will not falsify the greenhouse hypotheses, however. The global climate is a complex system of energy transfers involving cloud formation, air currents, ocean currents, changes in rainfall and soil moisture, and storm frequency – as well as temperature change. An absence of global warming to date, then, does not necessarily mean that the climate is not being adversely affected by greenhouse gases. The climate change might be occurring in one of these other areas of the system.

To study these energy transfers, much effort has been spent in developing computer simulation models of Earth's climate. These "general circulation models" represent Earth's climate with a series of mathematical equations of the processes occurring in various spheres of Earth – the atmosphere, the oceans, the continental landmasses (the geosphere), the biosphere, and the cryosphere (ice caps and glaciers). The behaviour of each of these areas varies considerably with respect to speed and complexity; for example, the geosphere and the crysophere affect climate greatly, but change very slowly, while the atmosphere and ocean surfaces can change rapidly. Models must capture this complexity for accurate representations.

Some components are incredibly complex. Consequently, modellers make a large number of simplifying assumptions about them. Particularly difficult to model are cloud formation, biosphere/climate interactions, and ocean currents; consequently, researchers remain largely uncertain of their behaviour. Since modelling the details of small-scale processes like those involved in cloud formation and ocean currents is also limited by computer power and expense, it is not attempted. Instead, these processes are treated as "black boxes" and statistical observations are inserted. This procedure is known as parameterization. Thus, for example, modellers collect data on general correlations between humidity and temperature levels, and assume that they are sufficient for modelling purposes. Thus, the need for detailed equations representing the physics of these relations is avoided. For example, while the Canadian Climate Centre model has the highest spatial resolution of any model, it does not include ocean currents.[30]

A major methodological objective of global circulation models is to represent the present climate – including seasonal changes, evaporation, and rainfall – and then to adjust the components of the model to represent changes in greenhouse gases. (A common model scenario assumes a doubling of carbon dioxide (or equivalent), while other models adjust the increase more gradually.) Unlike that of regional weather forecasting, the goal of climate modelling is not to predict the system's behaviour at any particular point in time but only the general behaviour of the system. Thus, the resolution of a climate model is intentionally lacking in detail. Global circulation models represent the atmosphere as a series of grid points on three-dimensional axes. The number of points is largely determined by computer power, because for each point several meteorological variables are calculated. For detailed, regional weather forecasting, these grid points are in close proximity. In contrast, for global modelling, the required resolution is much lower, and grid points may be several hundred kilometers apart with only 10–20 vertical levels.[31]

One climatologist has claimed, ironically, that "the greenhouse effect is the least controversial theory in atmospheric science."[32] What he means is that, while there are many uncertainties about whether global warming will be catastrophic, the general behaviour of the components in the model is not disputed. We know, from the analysis of ancient air found in bubbles trapped in glacial ice cores, that the concentration of greenhouse gases has increased. The warming effect of these gases is well understood. The ultraviolet rays of sunlight penetrate the atmosphere, strike Earth and are reflected back as infrared rays, which are then absorbed and trapped by the greenhouse gases in the atmosphere. We know that the greenhouse effect is what makes this planet habitable, and that the controversy is really about whether this effect will be increased and, if so, whether this increase will be detrimental to humans. We also know that some historical climate changes – for example, the end of the last ice age – are correlated with changes in greenhouse gas concentrations. (However, this correlation does not imply causation.)

The controversy lies in whether average global temperatures have already actually increased or will increase. The rate of change is also highly uncertain and yet crucial for ascertaining whether global climate change is a serious threat. The theory of the greenhouse effect is uncontroversial in the sense that everyone agrees that an increase in the concentration of greenhouse gases will affect the climate somehow. What *is* controversial about the theory is just what the consequences will be: how much warming and where? Will there be any negative feedback from the atmosphere, the oceans or the ice caps to mitigate any warming?

Evidence cited for the increase in global temperature consists in the recorded warming trend in recent global meteorological history (the hottest years on record have been in the last two decades), the observation that the average surface temperatures have increased by 0.3–0.6 °C in the last hundred years, the fact that Canadian lakes have an increasingly long ice-free season, and many other changes in the timing of plant and animal cycles such as flowering and egg-laying.[33] However, there is no evidence that these changes are directly linked to anthropogenic emissions; it might still be possible that the temperature increase is just part of normal global temperature variations.

Some climatologists who believe that Earth is warming claim that it is unlikely that such a warming trend could have occurred merely by natural processes: "with 99 percent confidence we can state that recent global warming is a 'real warming trend,' not one occurring by chance or accident."[34] Others, however, are not convinced: "recent warming is still within – although perhaps pushing – the upper limits of natural variability."[35] Even if there is a warming caused by anthropogenic emissions, its magnitude is not yet outside natural limits, and thus the existence of this warming cannot serve as evidence for the increased greenhouse effect hypothesis.

Even if the prediction of increased warming is accepted, however, it is not *obvious* that the predicted three or four degree temperature increase presents a serious problem for humans and other creatures. Warming might even benefit some regions without harming others. Winters and nights could be warmer without necessarily increasing summer or daytime temperatures. The growing season might be extended at high latitudes, and high carbon dioxide concentrations increase growth rates of many plants while simultaneously decreasing their need for water, thus making agriculture possible in semi-arid wastelands. Previously lifeless areas might become capable of sustaining ecospheres. Such changes might result in benefits in agriculture and forestry.[36]

Others argue that this optimism is too hasty. First of all, complex systems cannot be changed that simply. For example, even though the growth rate of plants might increase, pests too are likely to be more prolific. Though a slight increase in temperature might be beneficial in some areas were it to come on gradually, if it were to come on rapidly, ecosystems would not be able to adapt. Furthermore, even small changes in global temperatures can change global climatic *patterns*, resulting in increased frequency and severity of hurricanes, droughts,[37] and other weather disasters – what Bernard calls "climatic stress."[38] Thus, even a small temperature increase might present a serious problem. Analogies with past abrupt climatic changes – cooling at the end of the dinosaur era, temperature fluctuations due to enlargement and diminishment of ice-age glaciers, the 1930s drought in the US Midwest – indicate that a shift of only a few degrees can have severe consequences.

Second, the predicted increase of 1.4–5.8 °C over the next hundred years is a global *average*. Climate models aggregate the climate of various regions into one large grid and thus ignore regional differences. However, it is the larger temperature variations within the various regions that are the source of the environmental anxiety. The poles will get warmer, perhaps resulting in some melting of the ice caps and flooding of the world's coastal settlements, endangering an enormous number of lives.[39] Even as coasts are flooded, the interior of some continents will be stricken with drought, straining irrigation resources, harming wetlands, and increasing wind-erosion of the land.

Uncertainties are not confined to regional variation, however. The chain of consequences triggered by an increase in average global temperature might result in either an acceleration or mitigation of the warming trend. It is possible that the effects of some process act in such a way as to enhance that process. This is known as a positive feedback loop. For example, a positive feedback loop might be that warmer oceans would absorb less carbon dioxide, or they could release tons of the greenhouse gas methane stored in sea floor mud or permafrost, thereby causing further warming.[40] Either way, the warming effect could be enhanced by about 0.5°C per year.[41] Negative feedback loops, on the other hand, serve to reverse or slow down a process. In this case, it might be that an increase in global temperature would result in more bright cloud formation, which in turn could mitigate the warming effects by decreasing the amount of sunlight that reaches Earth. Once again, however, the pattern of cloud formation would have regional variations and would have different effects in different areas.[42] Clouds of ice crystals over the Arctic behave differently than clouds over the tropics with respect to how much heat is trapped or reflected.[43] The effects of clouds vary greatly with their brightness and structure. Clouds can deflect light and thus decrease warming, or act as an insulating layer, thereby increasing global warming. Cirrus clouds, which now cover approximately 16 percent of Earth, act as a blanket and can have a net warming effect, while marine stratocumulus clouds, which now cover approximately 34 percent of Earth, have a net cooling effect because their brightness reflects sunlight back into outer space. Slight differences between models in the way that the dynamics and distribution of these clouds are represented will result in large differences in predicted warming.[44] We also do not know whether the concentration of greenhouse gases will continue to increase or whether the deep ocean currents will absorb most of the greenhouse gases (although it is suspected that the rate of deep water absorption will decrease[45]). We think there must be a carbon sink somewhere because of the missing carbon problem. The concentrations of carbon dioxide in the atmosphere are not as high as estimates of carbon dioxide emissions, and we do not know where the missing carbon is going.[46] Other negative feedback mechanisms that would limit the effects of global warming have also been postulated. Polar ice caps might actually *increase* in area. Although the poles might get warmer, it might still be cold enough for snow. Higher average temperatures mean higher amounts of evaporation of water, and this could lead to a greater accumulation of snow. This increased area would mean a greater reflectivity of the sun's energy. This, in turn, would slow the warming.

Another complication that modellers must consider is the effect of sulphate emissions. The burning of fossil fuels, which is the major source of greenhouse gas emissions, is also a source of sulphate particle emissions. Sulphate particles in the atmosphere initiate a cooling process by reflecting light.[47] Researchers estimate that approximately 25 percent of the global warming effect can be mitigated by the presence of sulphate particles.[48] Ozone reduction might also indirectly cause cooling through complicated atmospheric chemistry leading to increased cloud formation.[49]

Modelling oceans is also complicated. Increasing water temperatures will change levels of salinity, biological activity, rates of carbon exchange between surface and deep currents, and much else.[50]

How these feedback loops will work is the largest source of uncertainty in global circulation models. Stephen Schneider concedes that "present models, crudely reproducing only average cloudiness, can say little that is reliable about cloud feedback – or about the many other feedbacks."[51] Similarly, an IPCC assessment of general circulation models concludes that "in their current state of development, the descriptions of many of the processes involved are comparatively crude."[52] (Although the most recent IPCC report claims that models are improving all the time.[53]) Even well-known feedback mechanisms, such as those between climate and vegetation, are not always included owing to limited computer resources.[54]

In the case of greenhouse models, there will be no one discovery that will confirm or falsify the models. In the ozone layer depletion case, as we saw, a single experiment confirmed, to the satisfaction of most researchers, the connection between chlorine concentrations and ozone depletion. However, in the global warming case a large number of climate variables is involved; the unfolding of global warming will not be a simple rise in average surface temperature. Confirmation of models that predict global warming will be a slow process of gathering data about many parts of Earth's climate over many years. (For example, some models predict an increase in precipitation above 30°N latitude, and a decrease below this latitude.) Research is ongoing, but it appears that some new studies hint that global warming will not be as great as was previously thought.[55] For example, currently estimated increases in sea level are not nearly as large as those once thought likely.[56]

Meanwhile, the actions recommended to avert this possible catastrophe will be much more costly than were required in the ozone-depletion case. Greenhouse gases are produced by routine and fundamental practices in transportation, industry, and agriculture. Reduction of emissions in these areas will require a much larger trade-off than was required in reducing CFC use. According to one estimate, even if we were to replace every coal and oil-burning electricity generating plant with one that produces no carbon dioxide, total carbon dioxide output would be reduced by only 25 percent.[57] Furthermore, because carbon dioxide resides in the atmosphere for long periods, even with a complete cessation of emissions today, about half of the recent increase in concentration would still remain in the atmosphere in one hundred years.[58] To stabilize greenhouse gas concentrations at current levels, reductions in use will have to be dramatic. In his book *The End of Nature*, Bill McKibben comments that "the sacrifices demanded may be on a scale we can't imagine and won't like."[59]

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What Is a Scientific Model, and What Do We Do with One?

In the previous chapter, we acquainted ourselves with four contentious models of global processes. In the next chapter, we will scrutinize the same four models to see whether any of them generate predictions reliable enough to support decisions about economic or political policies. In this chapter, we will try to understand the nature of models and how models are used in science. What is a scientific model, and what do we do with one?

The main function of scientific models is to provide predictions and what Mary Hesse calls "intellectually satisfying" explanations.[1] A scientific model is a representation of the workings of some system, a representation meant to explain the observed course of events and to provide predictions. The ultimate goal of a model is to supply enough understanding for us to be able to intervene in the system to achieve some end. We might model a traffic system in order to guide decisions about the best use of stop signs or one-way streets with the goal of obtaining safer and more efficient traffic flow. We might model the population dynamics of a wilderness system with the goal of preserving the elements of that system necessary for the survival of some species. We create a model in the hope that it may provide a good estimate of the time scales involved in a system, reveal general behaviour patterns in it, and identify the most sensitive points from which to influence that behaviour.

Hesse distinguishes three types of scientific models – physical models, analogies, and mathematical models. Some models are physical representations – for example, a wind tunnel containing a scale replica

Notes

PREFACE

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INTRODUCTION

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CHAPTER ONE

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CHAPTER THREE

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