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Global Environmental Forces

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Greenhouse warming is global in at least two respects. First, carbon dioxide (CO,) and the other gases released or withheld anywhere on earth disperse rapidly into the global inventory. The location of origin makes no difference. Second, the effect will be a change in global circulation of air and water. Although the mean rise in atmospheric temperature is commonly used as an index of climate change, the change in temperature differential between equatorial and polar regions may be a better measure of global environmental forces.

The standard point estimate of global warming for a doubling of the concentration of CO_2 in the atmosphere is 3°C [1]. But it is usually estimated that the warming in the polar regions associated with this three-degree average change might be eight or ten degrees, whereas the change in atmospheric temperature near the equator might be closer to one degree [1]. Offhand this sounds like a welcome dispersion of temperature change: it will mainly get warmer where it is already very cold and warm up the least where it is already hot. But more significant is that it is the temperature gradients between equatorial and polar regions that drive the winds, which in turn drive the oceans, and a change of seven or eight degrees in the mean temperature ***difference*** will change the atmospheric and oceanic circulation much more than would a uniform global rise in atmospheric temperature. Most climates may get warmer; some will undoubtedly become cooler. But the observed changes will include not only temperature and temperature variation from season to season and year to year, but also, and probably more importantly, the amounts, the seasonal distribution, and the year-to-year variation in rainfall, snow, wind, fog, sunlight, humidity, and storms.

For the purpose of comparing forthcoming changes in climate with changes experienced in the past, the mean global atmospheric temperature is probably not only a reliable index but also something of a measure of magnitude. Using the commonly accepted three-degree rise from a doubling of the atmospheric concentration as an approximation to what may be forthcoming, the ensuing temperature will not only be well outside the range of atmospheric temperatures experienced in the past 10,000 years but may be several times the range of temperature variation experienced in that time. This

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observation is frequently expressed, and correctly, as a change in climate greater than any that mankind has experienced since the dawn of history. It is expressed more accurately as changes in climates-plural not singular--because different climates around the globe will change differently.

Without belittling the unprecedented nature of such climate changes or the prospect of some change that is not gradual but catastrophic, it is fair to point out that most people will not undergo in the next 100 years changes in their local climates more drastic than the changes in climate that people have undergone during the past 100 years. No climate changes are forecast that compare with moving from Boston to Irvine, California, or even perhaps from Irvine to Los Angeles. The Goths and the Vandals, the Romans and the Vikings, the Tartars and the Huns migrated through more drastic changes than any currently anticipated; Europeans who migrated to North and South America similarly underwent drastic climate changes. In this country in 1860 barely 2% of the population lived outside the humid continental or subtropical climates; in 1980 the percentage outside these zones had increased from 2% to 22%.

Furthermore, the microclimates of urbanized Tokyo, Mexico City, and Los Angeles have not deterred their population growth; the microclimates of London and Pittsburgh changed dramatically during the century before 1950 and have changed again almost as dramatically since then. Even urbanization itself, without the associated air pollution, changes the conditions created by climate. Most Americans, Europeans, and Japanese never experience muddy roads anymore.

The expectation is that climates will change gradually, both over time and over space [2, Ch. 1–3]. The climate of Nebraska may gradually change into the current climate of Kansas, not into the climate of Massachusetts or Oregon. Climates will "migrate." This expectation is on the whole reassuring, but it could be mistaken. The models used in the computer simulation of climate may be incapable of producing discontinuities because the current state of meteorological knowledge is confined to continuous processes. There may be no reason to expect discontinuities, but the fact that the models produce no discontinuities may reflect an inability to design models based on the state of the art that can discover such phenomena.

Aside from a possible rise in ocean level, which I shall discuss presently, the most predictable physical and economic consequences of climate change will be in agriculture. By "predictable" I mean not that the actual changes can be predicted but that it can be reliably predicted that there will be changes. These will be changes in rainfall, winter snow for summer irrigation, humidity, daylight and cloud cover, and perhaps the health and comfort of livestock.

There is no reason to believe that the revolutionary improvements in agricultural productivity that have developed over the past 75 years, and that in many cases have spread worldwide, will not continue. Depletion of soils may continue, but control over plant and animal genetics and the possible production of new proteins may drastically change for the better what crops people will grow and what foods they will eat 50 or 100 years from now. An increase in the cost of food production by 5 or 10%, even 20%, which would be a somewhat extravagant estimate, may easily be offset many times over by another century's improvements in agricultural productivity.

There will undoubtedly continue to be parts of the world that are intractably poor and dependent for a livelihood largely on local production of food or other climatically dependent crops. These countries may have little of the capacity to adapt that the more advanced countries can afford. So even if the damage to food production may not average enough on a global scale to be cause for alarm-may not even be noticeable-there may be particular areas in which the damage to agriculture coupled with population growth could severely retard progress. (Population growth may be more serious.) This situation may demand foreign aid to the poorest countries. I would neither expect nor recommend foreign aid directly related to hardships induced by climate change, but rather aid to the poorest.

What I have said so far will sound to many readers as insufficiently alarmist. "Optimistic" it may appear. One reason for the unexcited tone, which I shall elaborate shortly, is pessimism, not optimism. I do not believe that serious measures will be taken over the next quarter century to curtail the emissions of carbon into the atmosphere. I do not believe that even an alarmist appraisal will lead to a substantial policy response. I therefore do not believe that exaggerating the dangers will serve a useful purpose.

But there is, I acknowledge, another reason why my assessment is so mild. As I mentioned earlier, I am attempting to assess predicted changes, and it may be that our climate models predict only what we understand well enough to include in the models. Maybe we are also good at adapting to phenomena we understand, as well as being good at predicting them; and the ones we do not understand well enough to predict will cause difficulty because we do not understand them well enough to adapt. In other words, there is bias in our assessment of dangers: those we understand well enough to perceive we understand well enough to overcome; those that we have no hints of may be the dangers we would least know how to meet and overcome. Reduced rainfall in Kansas 25 or 50 years from now we may adapt to with moisture-conserving agricultural techniques, genetically altered crops that require less moisture, or the acquisition and transport of water. The phenomenon is familiar, the adaptations are familiar, and the predictions are based on familiar principles of meteorology. The "collapse" of the West Antarctic Ice Sheet would be an altogether different phenomenon.

As recently as 15 or 20 years ago, the accepted estimates were that the grounded ice-ice resting on the sea bottom and rising a kilometer or more above sea level-might, with a warming of the oceans attendant upon a warming of the atmosphere, slide or glaciate into the ocean within 75 years, causing a 20-foot rise in sea level. Like seismology in response to the test-ban controversy of the 1950s, glaciology has advanced in the past decade or two, assisted by satellite sensing, and the currently accepted estimates are that if the grounded ice should be added to the ocean level it is likely to be gradual and to take several hundred years. The urgency of that particular danger is thus reduced by an order of magnitude (unless further rapid advances in the relevant glaciology bring comparable changes in estimates back in the opposite direction). What is worrisome is that there may be other phenomena, perhaps, like the ocean level, not being perceived as "climatic," that could be as devastating as a 20-foot rise in sea level and that will not, upon further inspection, yield to more benign estimates.

When asked for an example, I can of course protect myself by pointing out that predicting the unpredictable, foreseeing the unforeseen, especially as an amateur, cannot be demanded of me. But when I am in a mood to worry I think about possible changes in the Gulf Stream and the Japan Current. The current global circulation models, as I understand it, do not include changes in the direction and velocity of ocean currents, and I am not sure that enough is known about the response of ocean currents to changes in wind patterns to predict whether there may be catastrophes, that is, flip-flops from one equilibrium to another, rather than gradual change. Thus, there may be a missing feedback loop from warming to winds to currents to climate that, when added to the current models, will produce something more worrisome than the migration of the climate of Kansas to South Dakota.

As I said at the outset, the problem is global; and that is why it is exceedingly unlikely that anything substantial will be done to curtail fossil fuel emissions. Any nation that attempts to mitigate changes in climate through a unilateral program of energy conservation or fuel switching (or expensively scrubbing CO_2 from smokestacks) in the absence of some international rationing or compensation arrangement pays alone the cost of its program while sharing the benefits with the rest of the world. Consider the Federal Republic of Germany, which accounts for about 4% of the world's energy consumption and just about 4% of each of the three fossil fuels, coal, oil, and natural gas. If that country took the drastic step of reducing by one-third its consumption of fossil fuels, the cost in lost productivity and consumer welfare, even if it were done gradually over a period of two decades, could be equivalent to 3-4% of its gross national product, while the concentration of CO, in the atmosphere would be reduced by barely 1%. Even for the United States, the largest energy consumer of all, phasing in a one-third cutback in fossil fuel consumption over the next 20 years, at a cost perhaps equivalent to $150 billion or $200 billion per year at today's prices and income levels, would reduce emissions worldwide by less than 10%. The time to a doubling of CO_2 in the atmosphere might be reduced from something like 85 years to 80 years. I think it is a fair estimate that for no *individual* country, with the arguable exception of the United States, is it economical to curtail CO_2 emissions unilaterally in the interest of retarding climate change.

Any significant effort to curtail emissions would require an international rationing regime, covering the larger fraction of world energy consumption, to ration the consumption of energy, or the consumption of fossil fuels, or the consumption of carbon, in some manner that could confidently be expected to remain in force long enough to be effective, say 50 years or more. It would have to include the Soviet Union, it would have to include the People's Republic of China, and it may well have to include the Organization of Petroleum Exporting Countries (OPEC). It would require mandating compliance on the part of scores of nations that would greatly prefer to be outside the regime. And it would require for many nations trading urgently needed economic growth now for the dubious future benefits of a rationing scheme that depended on a more disparate membership than even that of OPEC. Eventually, because most of the world's known coal resources are in the Soviet Union, China, and the United States, the scheme would require those three nations to collaborate effectively and indefinitely as a cartel.

The political likelihood of solid and confidently expected collaboration of that kind would be approximately zero if energy were a homogeneous commodity consumed uniformly worldwide. But to put in effect a rationing scheme the impact of which will begin to hurt and be effective only after several decades of energy growth would require dealing with economic growth itself, and that in turn requires attention to things like population growth [3, 4]. Do the Chinese claim that a policy of zero population growth is more than sufficient as a curtailment of energy use and that their country should therefore be exempt? Do the countries in the Organization for Economic Cooperation and Development participate as a unit, negotiating long-term shares in energy growth? Is there any chance they could be more successful than they have been with defense budgets, oil imports, or agricultural trade?

My pessimistic conclusion is that nothing of the sort is going to happen. I do not believe the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in September 1987, is any harbinger for suppression of CO_2. Economically what is at stake is two or three orders of magnitude greater for fossil fuels than for chlorofluorocarbons (CFCs) and the prospects for technological replacement of CFCs are much brighter. (The Ozone Protocol does illustrate the need for worldwide collaboration to make restrictions worthwhile: the treaty takes effect only when ratified by nations representing two-thirds of world consumption.)

If world politics change as much in the next 75 years as in the past 75, a global fuel regime of some kind may become possible, but none is now foreseeable. If I am wrong, and world rationing of fossil fuels becomes economically and politically feasible, we shall still face the prospects for climate change. There is absolutely no possibility that fossil fuel emissions can cease altogether in the foreseeable future, and even the most optimistic could hardly hope that fuel emissions would stop growing within the foreseeable future. A most ambitious goal might be to reduce by half the growth rate in fossil fuel emissions. (As the fraction of fossil fuels represented by petroleum and natural gas declines over the coming century, fossil fuel consumption will have to increase at less than half the unrestricted growth rate in order that carbon emissions be only half what they might otherwise be.) A not unreasonable estimate, for purposes of illustration only, of growth in fossil fuel consumption over the next half century might be 2% per year, a rate at which the atmospheric concentration of CO_2 might double in about 85 years, reaching 50% elevation in about 50 years. Holding emissions to 1% growth would carry us beyond the middle of the next century before we reached concentrations half again as great as today's. The implied curtailment in emissions, at 1% compared with 2%, would be 10% at the end of the first decade, 25% at the end of three decades, and 40% by the end of five decades. That seems to me to be the outside limit to what might be economically acceptable worldwide. (How that 40% aggregate curtailment would be shared among consuming nations I hesitate to conjecture.)

National programs to phase in nuclear power to replace fossil fuels for electricity, even for the production of hydrogen fuels, may again become popular. But it is still hard to measure the half-life of anxiety resulting from the accidents at Three Mile Island and Chernobyl. Any new reactors will have to be economical as well as clean. Cutting the growth of emissions from 2% to 1% may well require all electric power capacity in the future to be nuclear.

Energy conservation measures deserve emphatic attention, but investments in conservation will mainly be limited to what the private economy finds economical. National or international policy will probably be limited to research, development, demonstration, and technology transmission. Energy-efficient investments may yet get a boost from another doubling or more of the price of crude oil, but that is probably not a boost to be hoped for.

What else may be done to cope with the greenhouse problem? CO_2 can be removed from the atmosphere by increasing the mass of living vegetation or by "refossilizing" timber, burying it underground or in the ocean or coating it so that it cannot oxidize. And CO_2 can be scrubbed from smokestacks at very substantial expense. Probably at enormous expense, some attenuation could be achieved in this fashion. (Some small increase in the carbon density of forests may result naturally from the enhancement of CO_2 in the atmosphere.) The concentration of CO_2 will therefore certainly increase, and at an increasing rate, and I consider it unlikely that we shall be rescued much before the concentration has nearly doubled.

The main response will be adaptation, and most of that by ordinary people and business. Some of the adaptation will be by governments, but by local and regional governments as much as national governments. There will be changing climates to cope with, changing urbanization, changing population densities, and in most countries probably drastic changes in the ways that people live and work and transport themselves, perhaps significant changes in what they eat. Much of the adaptation will seem generally "environmental" rather than specifically climate oriented. And, of course, there is continuous adaptation to climate even when it is not changing: we change the technology and the efficacy with which we heat ourselves and cool ourselves and clean our air and protect ourselves from storms and cope with droughts and floods and dispose of snow. The pace of change may be such that people will find themselves adapting to *climate* rather than to *changing climate*. Just as businesses shift to take advantage of better productive climates, they will keep shifting to better climates with perhaps small regard for the prospects of changing climates in given locations.

There remains to be discussed a response to climate change that receives so little attention that it deserves emphasis here-direct intervention in weather and climate. When Thomas F. Malone was chairman of the Committee on Atmospheric Sciences of the National Research Council, he wrote, 20 years ago, "The possibility that large effects may be produced from relatively modest but highly selective human interventions opens up the possibility that weather and climate modification may some day be operationally feasible" [5, p. 1136]. And of the modification of hurricanes he said, "If five years are allowed for the development of an adequate mathematical model, five more years for assessing the consequences of interventions of various kinds, and then ten years of field experimentation for validation, it seems unreasonable to expect much before 1990, with the probabilities fair to good that a proven technology will exist by the year 2000." He added, "The probability of success in broad climate modification is likely to exceed 50 percent by the year 2018" [5, p. 1138], that being the 50-year mark from the time he wrote.

Most experiments with weather modification or with changing geographical features that may lead to climate change have been local and regional. That has been true of cloud seeding and would be true of the manipulation of hurricanes. In a discussion of greenhouse warming, the possibility of global intervention has to be considered. An important kind of human intervention in global climate may be efforts to change the radiation balance itself. We know it can be done: we are doing it. That is what the greenhouse discussion is all about. The fact that we are doing it unintentionally, and the fact that the consequences may not be welcome, do not contradict that we know how, at some expense if necessary, to change the world's climate more than it has changed in the last 10,000 years.

Warming the atmosphere currently is more economical than cooling it because it happens as a by-product of energy consumption that would be costly to reduce or terminate. If we were faced with a "little Ice Age" over the next century, we might be glad to get some of that CO_2 in the atmosphere at no cost and without having to negotiate climate change diplomatically.

But we know that, in principle, cooling could be arranged. Volcanic eruptions have done it. Discussions of "nuclear winter" took seriously the possibility that human activity might lower global temperatures cataclysmically. Considering the development of nuclear energy in both its explosive and its controlled uses and the feat of landing a team on the moon and returning it safely, and that we now know how to warm the earth's atmosphere and possibly to cool it (though through unacceptable means), we should not rule out that technologies for global cooling, perhaps by injecting the right particulates into the stratosphere, perhaps by subtler means, will become economical during coming decades.

A more benign example, compared with nuclear winter or induced volcanic eruptions, may be the manipulation of cloud cover. Let me again quote Thomas Malone [5, p. 1135].

> A characteristic of the atmosphere that frustrates the weather forecaster while providing a basis for optimism on the part of the weather modifier is a tendency for the processes in the atmosphere to

> demonstrate certain traits of instability. For example, a small puffy-type cloud may grow to a towering thunderstorm in a matter of hours; a gentle zephyr in tropical latitudes may develop into a "killer" hurricane in a matter of days; and a small low-pressure center may grow to a vigorous extratropical cyclone within a single day. . An avenue may be opened up by which great effects may be produced from relatively modest but highly selective human interventions.

If somebody learned in the next 50 years how to affect the extent and global distribution of certain kinds of cloud cover, incoming radiation may become manipulable by nations, international agencies, or even interested private organizations, depending on the nature of the technology, its expense, and perhaps geographical considerations.

It is difficult to mention such a possibility without appearing to recommend it, or to use it as a "technological fix" in the future to divert attention from some need for immediate policy intervention. I am not recommending, I am predicting. Independently of CO_2, we have to consider that weather and climate modification may become feasible in a period of time no longer than the elapsed time since electronics, genetics, antibiotics, and nuclear fission were unimagined. The greenhouse warming may generate an interest among most nations in moderating the changed radiation balance, and if it proves more expensive to facilitate outgoing radiation than to obstruct incoming, there may be powerful motives for considering it. And if the technique for moderating incoming radiation were globally uniform or nearly so, an international agreement would have only to decide how to share the costs, a unidimensional problem compared with sharing the reduction of emissions.

If intervention is more regional than global, or global but not uniform in its distribution, intervention could become exceedingly controversial. Mexico and China are counting on those hurricanes-they are an essential source of rainfall for crops-whereas the Cubans, Filipinos, Japanese, and residents of the Texas coast would suppress them if they knew how.

In closing I must say a word about sea level. I believe the current wisdom is that we may be in for a rising sea level that could be on the order of a meter per century for several centuries [6]. Anything upwards of a meter, perhaps even half a meter, would primarily be due to the collapse of the West Antarctic Ice Sheet. The full 20-foot rise corresponding to the complete disappearance of that body of ice would put the White House rose garden under water, make Beacon Hill in Boston an island, and isolate the southern third of Florida by making the middle third disappear under water.

A country like the United States should be able to adapt (eventually by doing, perhaps, what the Dutch have been doing for centuries-constructing dikes). No such "easy" solution is available to a country like Bangladesh, which is densely populated in large areas that would be inundated by the full sea level rise, and which could not be protected with dikes. (If dikes were erected along the coastline to protect against seawater flooding, the area would simply be flooded with fresh water that could not flow out to sea).

If current estimates hold up, the potential devastation of rising sea level will mainly be 100 years away, and the government of Bangladesh should worry much more about population and productivity than climate change. If the more prosperous nations were prepared to help Bangladesh at great expense to themselves, aid now would probably appeal more to Bangladesh than heroic efforts to forestall floods a century hence. (That country already has floods to cope with in this century!)

Estimates of rising sea levels depend not only on thermal warming of the oceans, melting of glaciers, and what happens to the West Antarctic Ice Sheet; they can also depend on what happens to the Antarctic climate. There has been some conjecture that a warming of the South Polar air may lead to greater snowfall in Antarctica. The area of Antarctica is about one-fortieth the area of the oceans; a l-centimeter rise in ocean level would be offset by a 40-centimeter rise in the water content of the snowfall on Antarctica, or an average snowfall of 4 meters per year. Storing water as ice on Antarctica might be the ideal solution to the water-level problem. Even the people most offended at the thought of deliberately tampering with our climate to offset the greenhouse gases may agree that ieaming to make it snow on Antarctica is a worthwhile project for the next century.

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