MITIGATION OF CLIMATE CHANGE:
A SCIENTIFIC APPRAISAL

S. Fred Singer

INTRODUCTION

The global climate doesn't seem to be warming, much to the embarrassment of scientists who are banking their reputations on computer models that show large warming trends. What is more, the historic climate record, which includes a number of intervals warmer than those forecast by climate models[1] shows no evidence of environmental catastrophes. On the contrary, the overall consequences of warmer climates appear to be positive, much to the embarrassment of economists whose cost-benefit analyses automatically assume "disbenefits" from any warming. Politicians, of course, manage to avoid embarrassment by ignoring both science and economics. They preach policies of mitigation that range from trivial to fantastic, from economically neutral to extremely damaging. Here we assess a selected group of these policies, including the option most consonant with economic growth and market-driven innovation: adaptation to climate change.

The central problem is to explain the growing discrepancy between theoretical models and actual observations.

CLIMATE MODELS ARE NOT TRUSTWORTHY: WHY DO POLITICANS CONSIDER THEM "COMPELLING"?

International bureaucrats, prior to the December 1997 climate meeting in Kyoto, Japan, have pronounced global warming scientifically "settled." In an August 4, 1997 speech to various CEOs, President Bill Clinton asserted that the science is "compelling." In spite of a claimed consensus, however, most working scientists don't agree; to them the field is exploding with new questions that need to be addressed before we can confidently formulate policies.[2]

[1] The Mesozoic era, the age of the dinosaurs, appears to have been about 18o Fahrenheit warmer than our century. In previous interglacial periods, temperatures at high latitudes were 5.0 degrees to 11.0 degrees warmer than today; temperatures at middle latitudes, about 4.0 to 5.0 degrees warmer. At the height of the Climatic Optimum (4000 B.C. to 2000 B.C.), the world was four to five degrees warmer than now. Thomas Gale Moore, *Climate of Fear: why we shouldn't worry about Global Warming* (Washington, D.C.: Cato Institute, 1998), pp. 23-42. See also Hubert H. Lamb, "Climate: Present, Past and Future," *Fundamentals and Climate Now*, Vol. 1 London: Methuen, 1972.

[2] Broad, William J. "Another Possible Climate Culprit: The Sun." *The New York Times*, September 23, 1997; Citizens for a Sound Economy. *Survey of State & Regional Climatologists*. American Viewpoint, Inc.: Alexandria, Virgina, 1997; Cutler, Alan. "The Little Ice Age: When Global Cooling Gripped the World." *The Washington Post*, August 13, 1997; Kerr, Richard A. "Greenhouse Forecasting Still Cloudy." *Science*, 276, 1040-1042, 1997; Hoyt, D.V. and K.H. Schatten. *The Role of the Sun in Climate Change.* Oxford University Press: New York, NY, 1997; Calder, Nigel. *The Manic Sun: Weather Theories Confounded*. Pilkington Press: London, UK 1997.

Even those who accept model results have argued that delaying restrictions on greenhouse gas emissions for 10 years or more will have little effect on an ultimate temperature rise.

The central problem, certainly, is to explain the large and growing discrepancy between theoretical models and actual observations. The models give varying estimates for a future warming in the year 2100 – from as low as 1.0 degree C to beyond 5.0 degrees C, depending upon assumptions about energy scenarios and the details of atmospheric physics. The United Nations' Intergovernmental Panel on Climate Change quotes 0.2 to 0.3 degrees C per decade as a “best” estimate for a current warming trend.[3] By contrast, observations since 1979, from weather satellites and also from balloon-borne radiosondes, show a slight cooling trend.[4]

Many questions can, and should, be raised. Why do the models differ so much among themselves? Can any of them be considered trustworthy, in view of the striking disparity with observations?[5] And why should we base policies on computer models of the atmosphere that have proven themselves to be invalid?[6]

These questions are not likely to be settled very soon. Even with faster computers on the horizon, the task of accurately modeling the distribution of cloudiness, the distribution of water vapor (which is the major greenhouse gas), the atmosphere’s interaction with the ocean, and the influence of solar variations, is indeed daunting. Even those who accept model results have argued that delaying restrictions on greenhouse gas emissions for 10 years or more will have little effect on an ultimate temperature rise.[7] Greenhouse gases persist in the atmosphere a long time; whether we start reducing emissions now or a decade from now won’t change long-term concentrations by much. In that case, a delay would certainly permit a lower-cost approach to emission reduction, should that be necessary. Delay would allow business to replace capital equipment at the end of its natural lifetime rather than on an artificial, bureaucratically-imposed deadline.

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[3] IPCC Working Group I. “Climate Change 1995: The Science of Climate Change,” J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.). Cambridge University Press, Cambridge, UK, 1996.

[4] Spencer, R.W., and J.R. Christy. “Precision and Radiosonde Validation of Satellite Gridpoint Temperature Anomalies. Part II: A Tropospheric Retrieval and Trends during 1979-90.” J. Clim., 5, 858-866, 1992. Singer, S.F., Hot Talk, Cold Science: Global Warming's Unfinished Debate, (Oakland, CA: The Independent Institute, 1997).

[5] A few years ago, slight changes were made in the treatment of clouds in models run at the U.K. Hadley Centre for Climate Prediction and Research, caused the models’ response to a doubling of carbon dioxide to drop from 5.2 degrees C to 1.9 degrees C. An article in *Science* (Kerr, 1997) explained, “Other models of the time also had a wide range of sensitivities to carbon dioxide, largely due to differences in the way their clouds behaved. That range of sensitivity has since narrowed, says modeler and cloud specialist Robert Cess of the State University of New York, Stony Brook, but ‘the [models] may be agreeing now simply because they’re all tending to do the same thing wrong. It’s not clear to me that we have clouds right by any stretch of the imagination.’”

[6] Balling, Robert Jr., “Global Warming: Messy Models, Decent Data, and Pointless Policy,” *The True State of the Planet*, Ronald Bailey, Ed., (New York, Free Press: 1995); Roy Spencer, ???, *The Costs of Kyoto*, (Washington, D.C., Competitive Enterprise Institute: 1997).

[7] See, Schlesinger, M.E., and X. Jiang. “Revised projections of future greenhouse warming.” Nature, 350, 219-221, 1991 and Wigley, T.M.L., R. Richels and J.A. Edmonds. “Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations.” *Nature*, 379, pp. 240-243, 1996.

WARMER CLIMATES ARE BENEFICIAL; SO IS MORE CARBON DIOXIDE

In addition to purely scientific climate questions, there are uncertainties about the impacts of a possible warming. While politicians and much of the public automatically assume that the consequences of any warming will be harmful, the historic record and detailed analyses show that this is unlikely. Contrary to public pronouncements by the greenhouse lobby, even climate modelers state that, should global warming occur, severe storms should diminish in both frequency and intensity.[8] Such a warming, occurring mainly at night and during the winter at high latitudes, should benefit agriculture by creating fewer frosts and a longer growing season. The increased atmospheric carbon dioxide (CO_2) will certainly speed up growth and reduce evapo-transpiration from plants, thereby also reducing their need for water.[9]

Even the feared sea-level rise may not materialize. New evidence supports the opposite conclusion, namely that a warming will reduce sea-level rise by transferring water from the ocean to the polar ice sheets through increased ocean evaporation and precipitation.[10] Because average temperatures in the polar regions would remain well below the freezing point, increased precipitation there would take the form of snow and, thus, thicken the ice sheets.

Even the feared sea-level rise may not materialize. New evidence supports the opposite conclusion, namely that a warming will thicken the ice sheets.

In addition, historic evidence demonstrates that warmer periods have generally been beneficial for mankind, while colder periods have caused famines and disease.[11] The first Climatic Optimum of 5000 B.C. to 1000 B.C. accompanied – and encouraged – the birth of civilization. The warmer climate promoted the development of agriculture, which in turn made possible the expansion of industry and trade, the founding of cities, and an increase in human population. The Dark Ages (500 A.D. to 1000 A.D.) were dark partly because the climate was cold and damp. Inclement weather facilitated the spread of plagues and depressed agriculture, reducing population. The medieval warm spell or Little Climate Optimum (1000 A.D. to 1300 A.D.) was a period of improved health, revitalized agriculture and trade, cathedral building, and surging population growth.[12]

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[8] Landsea, C.W., N. Nicholls, W.M. Gray and L.A. Avila. "Downward trends in the frequency of intense Atlantic hurricanes during the past five decades." *Geophysical Research Letter*, 23(13), 1697-1700, 1996; Zhang, Y. and W.C. Wang. "Model-simulated Northern winter cyclone and anti-cyclone activity under a greenhouse warming scenario" *Journal of Climate* 10, 1616-1634, 1997.

[9] Idso, S.B. *Carbon Dioxide and Global Change: Earth in Transition.* IBR Press: Tempe, Arizona, 1989; Wittwer, S.H. "Flower Power: Rising Carbon Dioxide Is Great for Plants." *Policy Review*, Fall 1992, pp. 4-9.

[10] Singer, S.F. "Global Warming Will Not Raise Sea-Levels" Abstract for Fall Meeting of the AGU; submitted for publication, 1997. See also *Hot Talk, Cold Science*, p. 18.

[11] Moore, Thomas G. "Global Warming: A Boon to Humans and Other Animals." Hoover Institution, Stanford University, 1995.

[12] See also Moore *Climate of Fear*.

Finally, it seems to have escaped notice that the ultimate objective of the Climate Treaty is nowhere scientifically defined. Article 2 of the Treaty calls for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." What does that mean?

Two Swedish scientists, Azar and Rodhe, argue that until proven otherwise, we must assume that a temperature rise of 2.0 degrees C is "dangerous."[13] They offer no evidence for this assertion, however, except for citing an obscure Swedish report. They totally ignore the fact that the Earth's climate has varied by more than two degrees C during recorded history, as established by studies of ocean sediment cores. Azar and Rodhe further conclude that the present level of CO_2 is "dangerous;" they consequently propose stabilizing CO_2 at a lower level than the present one, which would involve cutting emissions by more than 70 percent worldwide! An analysis of the historical climate record, however, suggests the opposite; climate was more variable – and therefore more "dangerous"– during the recent ice age, when CO_2 levels were considerably lower than today.[14]

Historic evidence demonstrates that warmer periods have generally been beneficial for mankind, while colder periods have caused famines and disease.

THE POLITICAL QUANDARY: FOUR BROAD POLICY OPTIONS

The absence of any observed warming and of a defined goal for the Climate Treaty certainly creates a problem for politicians; they must persuade citizens to make major sacrifices to meet a non-existent threat that cannot be demonstrated and exists only on computer printouts. They are asked to weigh speculative damages of a possible warming against the certain costs of emission controls.

Nevertheless, even with the demonstrated absence of current warming, and with likely benefits should warming occur, we face a situation in which atmospheric CO_2 levels are increasing at a rate of 0.4 percent per year, and methane about twice as fast.[15] Politicians and the public need to know what can be done to mitigate any climate warming and/or reduce the growth of greenhouse gases, should that be desired.

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[13] Azar, C., and H. Rodhe. "Targets for Stabilization of Atmospheric CO_2." *Science*, 276, 1818—1819, 1997.

[14] Singer, S.F., "Unknowns About Climate Variability Render Targets Premature," *Eos* 78, p. 584 1997; also *Eos* 79, p. 188, 1998. Keigwin, L.D., "The Little Ice Age and Medieval Warm Period in the Sargasso Sea," *Science*, 274, 1504-1508, 1996; Stager, J.C. and P.A. Mayewski, "Abrupt Early to Mid-Holocene Climactic Transition Registered at the Equator and the Poles." *Science*, 276, 1818-1819, 1997; deMenocal, P. and G. Bond, "Holocene Climate Less Stable Than Previously Thought." *EOS*, 78, 447, 1997.

[15] Vincent Gray, "Climate Change 95: An Appraisal," *New Zealand Science Review* 53(4), 1996. Reprinted by The Heartland Institute, September 10, 1997, pg. 7-10.

There are general sets of policies that can be followed:

1) Cooling the climate.
2) Reducing emissions.
3) Sequestering atmospheric carbon dioxide.
4) Adapting to climate change.

Cooling the climate: A number of schemes have already been proposed for artificially changing the climate.[16] While all of these are physically possible, some of them are more speculative and costly – and certainly not feasible in the near future. They fall into three categories: a) increasing the reflecting power (albedo) of the Earth's surface or atmosphere; b) reducing the incident solar energy to the earth's surface; c) modifying the circulation of the atmosphere or ocean.

Affecting the atmospheric circulation is both difficult and uncertain because of our lack of understanding of all the consequences.

Increasing the reflecting power of the Earth's surface does not appear to be a promising line to follow. Seventy percent of the Earth is covered by oceans, which have an albedo of only nine percent. Floating large white plastic platforms would certainly increase the albedo, but does not make economic or political sense; it would be construed as pollution, and rightly so. Similar objections could be made to increasing atmospheric aerosols or releasing reflective particles into the stratosphere. These processes, of course, occur naturally when volcanoes deposit particulates into the atmosphere, or when sulfur-containing fuels are burned, creating sulfate aerosols.

To reduce solar energy reaching the Earth's surface, the only method that can claim to be ecologically sound is to launch light-reflecting or absorbing surfaces into space—beyond the atmosphere. When combined with the concept of converting solar energy into electricity, such structures, though costly, may make economic sense. Many studies have been published on solar power supplies in space, but the economics has never been persuasive. When the benefits of climate control are added, however, the economics may improve.

Affecting the atmospheric (or oceanic) circulation is both difficult and uncertain because of our lack of understanding of all the consequences; but the subject has always held great fascination for geo-scientists. It has been recognized that there are sensitive "pressure points" where ocean circulation might be affected. A recent paper, for example, discusses how diversion of fresh water because of the Aswan Dam would increase the salinity of the Mediterranean; the outflow of more saline (and heavier) water through the Straits of Gibraltar would then affect North Atlantic Ocean circulation, the Gulf Stream, and climate.[17]

[16] National Academy of Sciences 1991. *Policy implications of greenhouse warming: Mitigation, adaptation, and the science base,* Washington DC, National Academy Press.
[17] Johnson, R.G., "Climate control requires a dam at the Strait of Gibraltar." EOS, Trans. Am. Geophys. *Union*, **78**, 227-281, 1997.

It is not generally recognized that over-conservation which insists on replacing existing capital stock with more energy-efficient equipment, wastes energy – just like under-conservation.

Climate could be changed through a modification of atmospheric circulation, affecting either cloudiness or the distribution of water vapor, especially its vertical distribution. One method of affecting one, or both, of these quantities might be through changes in the stratospheric ozone layer. Recent studies suggest that ozone layer changes can affect atmospheric circulation.[18] And there are a variety of ways whereby one can change the total amount of ozone or its horizontal or vertical distribution. Everyone is familiar with methods for destroying ozone in different layers of the stratosphere; but the solar mirrors, referred to above, can also be used to enhance a portion of the solar radiation, thereby creating more ozone in the upper atmosphere.

To sum up: All sorts of speculative schemes have been suggested and will probably continue to be put forward. Many of them are worthy of research support; a few of them may even justify pilot experiments. Some may have undesirable side effects that need to be fully investigated.

Reducing emissions: There are, again, several options. The most benign method, certainly, is energy conservation and a more efficient use of energy through improved capital equipment or processes. In principle, conservation and energy efficiency save not only energy but also money; over time, this has been the main impetus behind such improvements. Problems arise only when efficiency increases are forced through arbitrary standards. A classic example is automobile fuel efficiency, which has increased up to a point because of a public demand for better gasoline mileage. But the demand for roominess and power has also increased the use of pickup trucks and sports vehicles that have relatively poor fuel efficiency.

-It is not generally recognized that conservation can be carried too far. Over-conservation, which insists on replacing existing capital stock with more energy-efficient equipment, wastes energy – just like under-conservation. It leads to the abandonment of energy-imbedded equipment and replaces it with equipment that requires energy to construct. As a general rule of thumb, one should not abandon equipment unless the energy savings from replacing it allow a pay-back in less than three to five years. If the payback period is too long, then energy is surely being wasted.

A different approach to reducing emissions of carbon dioxide is to change to non-fossil-fuel sources of energy: hydroelectric, nuclear, or various kinds of solar-derived sources. Hydroelectric power sources are well established, but require much energy to build, are very site-specific, and cannot be expanded indefinitely as demand grows. Furthermore, they have led to various ecological problems, particularly with fisheries. As a result, the Federal Energy Regulatory Commission is now engaged in tearing down some small privately-owned hydroelectric projects.

[18] Haigh, J.D. "The impact of solar variability on climate." *Science*, 272, 981-984, 1996.

Nuclear energy, of course, has problems of its own; they are mainly political not technical, and might diminish with a good public education program. Nuclear energy is generally safer, less polluting, and often cheaper than electric power systems based on fossil fuels. Since the cost of nuclear electricity is mainly in the capital cost, rather than in the cost of the uranium fuel, economies in construction are particularly important.

Nuclear power can be quite economic; for example, in France, plant design has been standardized, and the construction time has been compressed into five years or less. In the United States, litigation has often extended construction times to more than a decade, incurring huge interest costs. In addition, the Nuclear Regulatory Commission has frequently required post-facto construction changes based on insubstantial safety considerations, further raising the cost.[19] The current concerns of spent-fuel disposal and decommissioning of plants add very little to the cost, but figure highly in the public debate.

Who will monitor international trades to discourage collusive arrangements between a nation's companies and its environmental authorities to undercount emissions?

Solar energy is everyone's favorite. It seems to have few detractors. But its high capital cost makes it uneconomic, except in specialized applications. A special problem is the storage of energy, needed to supply power at night or on cloudy days. If there exists a large electric grid system, it can furnish storage for a certain amount of solar photo-voltaic and wind energy, thus eliminating this large cost factor. It is not likely, however, that any of the solar power systems can become a major supply source for electricity in the near future.

A third method of limiting emissions (preferred by regulators) simply tries to reduce the amount of fossil-fuel burning by rationing or by energy taxes. There are many schemes being discussed, including one that involves both rationing and a form of taxation. There are difficulties with all of these schemes in deciding upon an equitable distribution of energy, in monitoring its use, and in enforcing limits on fuel burning. These problems are all present for rationing, but are only partially relieved when demand is limited by taxation.

A scheme currently in favor would assign an emission quota to each nation – clearly a euphemism for rationing – but permit the buying and selling of unused emission permits, a kind of legalized black market. The initial problem, of course, arises with the allocation of national quotas. Should they be based on present energy consumption, on the 1990 level, or on some hypothetical future level extrapolated from population growth? Should a quota be assigned for carbon dioxide emissions only, or for methane, nitrous oxide, and other greenhouse gases as well? And should the per-capita

[19] Cohen, B.L. "Nuclear Power Economics and Prospects" in *Free Market Energy: The Way to Benefit the Consumer* (S.F. Singer, ed) pp.218—251, Universe Books, New York, 1984.

consumption of developing nations be set at some higher level than the present one; if so, which level?

Nor are these the only issues that must be resolved. To whom should the quotas be allocated – to oil companies that sell petroleum products (e.g. gasoline) into the marketplace or to business and household purchasers of transportation fuel; to coal, oil, and natural gas companies that supply electric utility companies or to the utilities generating electric power? Who will monitor international trades to discourage collusive arrangements between a nation's companies and its environmental authorities to undercount emissions? Will an international authority have to be created to enforce compliance and punish treaty violators?[20]

A technique analogous to afforestation, but economically more attractive, is to speed up the natural absorption of CO_2 into the ocean.

The process is clearly political and may do little to cut total global emissions; more likely, it will create a permanent entitlement program which funnels money from industrialized nations needing emission permits to developing nations willing to sell. It may even have the perverse effect of keeping developing nations from developing, if their government officials decide that the transferred funds can be put to a "better" use, like building showy luxury projects or diverting it into foreign bank accounts. Even if the money is not squandered or misappropriated, it is likely to nurture a huge bureaucracy that could seriously throttle free enterprise and economic development.

Of course, emissions trading is really a hidden energy tax for industrialized nations. Whoever buys the emission permits, whether electric power companies or oil firms, they will have to pass the cost along to the consumer. And if the protocol resulting from the climate treaty aims to stabilize the 1990 atmospheric concentration levels, then CO_2 emissions *worldwide* would have to be cut by 60 to 80 percent. Just keeping emissions at the 1990 level might require a carbon tax of $100 a ton or more, and would lead to corresponding increases in energy prices.

But these price increases may not be enough to suppress demand. After all, raising gasoline prices by 26 cents a gallon will hardly reduce the demand for driving. For the average motorist, fuel cost is a small fraction of the total cost of automobile transportation, of the order of 20 percent. The price of gasoline would have to go up by several dollars to make a real impact on driving habits.

Worst of all, if emissions were to be limited to 1990 values – or even to values 10 to 20 percent lower – atmospheric concentrations will still

[20] Fang, W.L. "Controlling Carbon and Sulphur: International Investment and Trading Initiatives," 11th International Conference, convened by the Royal Institute of International Affairs in association with the British Institute of Energy Economics and the International Association for Energy Economics, December 6, 1996, pp. 3-10.

increase, albeit somewhat more slowly. Stabilizing *concentration* of CO_2 at the present level requires emission cuts of the order of 70 percent worldwide.

To sum up: Controlling emissions, by whatever method, is extremely costly, distorts economic decisions, destroys jobs, is difficult to monitor, and practically impossible to enforce. It is likely to create huge international bureaucracies and police forces, damaging not only industrialized countries but certainly coal and oil exporters, and most of the developing countries, since they depend on trade with the industrialized nations.[21] And controls would do little good unless emissions worldwide are cut drastically—not just by 10 to 20 percent.

Sequestering atmospheric CO_2: Removing CO_2 from the atmosphere can be done by physical methods or biologically. The former have been studied by engineering firms and are judged to be uneconomic under current conditions. Biological sequestration can be done by land-based plants or by biota in the ocean.

While it may never be necessary to reduce atmospheric CO_2, it will be comforting to know that we have the technical capability to do so.

The best-studied scheme involves setting up giant forest plantations that can extract CO_2 from the atmosphere. The process is straightforward in that one has to select fast-growing tree species, and find locations where land costs and labor costs are reasonable. A good compilation of the current state of knowledge has been presented by IPCC Working Groups II and III.[22] Unfortunately, cost estimates vary widely (see Appendix) and go up rapidly as suitable land becomes scarcer. This is likely to happen because the areas involved are truly very large. If one uses as a rough guide one ton of carbon sequestered per hectare per year, absorbing current emissions would require planting an area of 4,500 x 4,500 miles. Although some attempts have been made by individual firms to plant forests to offset their own CO_2 emissions, forest-based sequestration of atmospheric CO_2 has not been pursued on a large scale.

A technique analogous to afforestation, but economically more attractive, is to speed up the natural absorption of CO_2 into the ocean. Currently, much of the world's oceans is a biological desert. Even though many of these areas have adequate supplies of the basic nutrients, nitrates and phosphates, they lack essential micronutrients like iron. Ocean fertilization[23] has been widely discussed among scientific specialists, with experiments

[21] Montgomery, W.D. "Impacts of Annex-I Country Commitments on Non-Annex-I Countries," Workshop on the Environment, Vienna, February 20, 1997; "Global Impacts of a Global Climate Change Treaty," in Jonathan H. Adler, ed., *The Costs of Kyoto: Climate Change Policy and its Implications* (Washington, DC: The Comptitive Enterprise Institute., 1997).

[22] IPCC Working Group II. "Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses." R.T. Watson, M.C. Zinyowera, R.H. Moss and D.J. Dokken (eds.). Cambridge University Press, Cambridge, UK, 1996; IPCC WGIII. "Climate Change 1995: Economic and Social Dimensions of Climate Change." J.P. Bruce, H. Lee and E.F. Haites (eds.). Cambridge University Press, Cambridge, U.K., 1996.

[23] McElroy, M.B. "Marine biological controls on atmospheric CO_2 and climate." *Nature*, 302:328-29, 1983.

proposed by the late John Martin[24] and endorsed by the late Professor Roger Revelle, director of the Scripps Oceanographic Institution in La Jolla, California. With the completion and publication of the successful IronEx-II test it now makes sense to consider ocean fertilization as a viable candidate for sequestering atmospheric CO_2.[25]

The ocean fertilization experiments, specifically the IronEx-II test, show that, in the equatorial Pacific Ocean at least, the growth of phytoplankton can be dramatically increased by the addition of minute quantities of inorganic iron to surface water. In common with the Southern Ocean, and, to a lesser extent, parts of the northeast Pacific, these waters are termed "high-nutrient, low-chlorophyll" (HNLC), meaning that the normal nutrients are found at the surface, but are not useable by plankton. Addition of the micronutrient iron permits uptake of these unused nutrients and an associated amount of inorganic carbon by an expanding plankton population.

It is difficult to justify major expenditures to address climate change in the presence of other societal needs, such as improved health care, adequate nutrition, sanitary drinking water, education, and personal and public safety.

A large-scale demonstration is essential, building on the scientific success of IronEx-II. It would prove the technical and economic feasibility of lowering the atmospheric CO_2 content at a fraction of the cost now contemplated for emissions reduction. (See Appendix.) While it may never be necessary to reduce atmospheric CO_2, it will be comforting to know that we have the technical capability to do so.

ADAPTION TO CLIMATE CHANGE: THE BEST INSURANCE POLICY

It is a fundamental principle of public policy that problems that are the most important and can be reduced, if not eliminated, at the least cost to society should be given the highest priority and dealt with first. Accordingly, one must address the question: How important is a possible climate change—above and apart from the major variations of natural origin, compared with other agents of future global change?

It is reasonably certain that any effects of human-induced climate change will be minor compared to other sources of change over the next century. Climate is important mainly because of its effect on natural resources, such as water, land, plants, forests, habitats, and other biological resources, and on human activities, such as agriculture, forestry, human settlements, and

[24] Martin, *Journal of Oceanography*, 4, 52-55, 1990; Martin, J.H., et al. "The iron hypothesis: Ecosystem tests in Equatorial Pacific waters." *Nature*, 371, 123-129, 1994).

[25] See the October 10, 1996 issue of *Nature*, 383. K.H. Coale, et al, "A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean," 495-501; M.J. Behrenfeld, et al, "Confirmation of iron limitation of phytophlankton photosynthesis in the equatorial Pacific Ocean," 508-511; D.J. Cooper, et al, "Large decrease in ocean-surface CO_2 fugacity in response to in situ iron fertilization," 511-513; S.M. Turner, et al, "Increased dimethyl sulphide concentrations in sea water from in situ iron enrichment," 513-517.

recreation, which depend on these natural resources. Based upon existing assessments, human-induced climate change over the next one hundred years will be much less important to the environment than the other agents of global change, such as population growth, economic growth, and technological changes.[26]

It is difficult to justify major expenditures to address climate change in the presence of other unmet societal needs, such as improved health care, adequate nutrition, sanitary drinking water, education, and personal and public safety. If, as has been argued here, climate change is a minor problem compared to other societal problems, then adaptation becomes the preferred option; one can then devote any resources thus saved to more urgent problems. Even if a significant warming were to occur, most of the current proposals being considered in Kyoto make no sense.

Adaptation to climate change is the normal response to seasonal and inter-annual variations of climate, and to many extreme climate events.

Adaptation to climate change is, of course, the normal response to seasonal and inter-annual variations of climate, and to many extreme climate events. Adaptation is generally easier for technologically advanced societies and for societies that have resources and can afford adequate housing, heating, air-conditioning, etc. It should be noted also, that throughout human history populations have adapted successfully to large permanent climate changes; for example, when Germanic tribes migrated from the frozen north to the Mediterranean. Historically, the Dutch have used sea walls to protect low-lying areas from storm surges; the same technique can be used to mitigate modest rises in sea level. The most serious climate threat to mankind may be the return of an Ice Age, following the end of the current warm interglacial period.

While adaptation to climate change may be problematic for natural ecosystems, the ability to adapt is, paradoxically, highest for those economic sectors and human activities which are most sensitive to climate change, mainly agriculture but also forestry, outdoor construction, recreation, etc. Because of their sensitivity to climate, such systems have always been heavily managed and have a long history of successful and rapid adoption of technological and management innovation.[27]

Some countries are already beginning to take advantage of research and technology to mitigate swings in temperature and precipitation. For example, the El Niño phenomenon has been so thoroughly studied that it can now be used in agricultural planning. Neville Nicholls of Australia's Bureau of Meteorology Research Centre, recently reported that suitable advance warning of shifts in weather patterns can result in "significant increase of profit (up to 20 percent) and/or reduction of risk (up to 35 percent)" when farmers adjust their crop management to match the forecasts. Such information

[26] Goklany, Indur M. "Adapting to Climate Change," forthcoming, pp. 11-15, 1997.
[27] Goklany, "Adapting to Climate Change," pp. 16-17.

could be used to mitigate warmer temperatures globally and any changes in precipitation that might occur.

Adaptation, with energy conservation and the encouragement of non-fossil-fuel resources, would help meet development goals by increasing the productivity or efficiency (per unit of land or water) of crops, livestock, forests, fisheries, and human settlements.

Throughout the global warming debate, politicians and bureaucrats have been guilty of systematically overestimating the negative impacts of climate change by distorting or ignoring the underlying science. Moreover, they have consistently downplayed adaptation, clearly the most desirable mitigation option. Instead, their emphasis has been on strategies to curtail CO_2 emission from fossil-fuel combustion and energy use thus compromising society's ability to cope with other global problems that require economic development. Emission controls, as planned, will not significantly reduce the concentration of atmospheric carbon dioxide. The main outcome of the Kyoto conference will be to expand the stranglehold of international bureaucracy.

APPENDIX

In the Table below, I have tried to estimate the costs of reducing the concentration of atmospheric CO_2 by different methods.

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- **By control of emissions:** (a)
  Typical cost ~ **$100-200** per ton of C emitted

- **By reforestation:** (b)
  Typical cost ~ $50 per ton of atmospheric CO2
  equivalent to **$25** per ton of CO2 emitted

- **By ocean fertilization:** (c)
  Assume 106 tons of iron (costing ~ $1 billion) can sequester 2x1010 tons of C into biomass and needs to be applied yearly. Assume that only 1% of C comes from the atmosphere, equivalent to reducing emissions by 2%, or 4x108 tons.

Therefore, estimated cost ~ $109/4x108 ~ $2.50 per ton of C

(a) Emission control costs are known to rise rapidly as the degree of control increases.[28] Besides, at the very best, emission control will only slow down somewhat the rate of increase of concentration.

(b) Estimated costs for sequestering CO2 vary widely, from $7[29] to $42-114[30]; see discussion in IPCC WGIII 1996 (pp. 352—355). The cost would rise as the degree of sequestration increases. [Removal of one ton per year is equivalent to reducing emissions by about 2 tons per year.] No allowance has been made for the economic value of the lumber harvested.

(c) Comparing the costs in the Table, it is clear that ocean fertilization has by far the lowest cost—$2.50 per ton of carbon —even if one assumes that the phytoplankton draws only one percent of carbon from the atmosphere and 99 percent from the oceans. In addition, sequestration by ocean fertilization should exhibit a linear cost curve, unlike forest sequestration or emission control. No allowance is made for the economic value of the fish resources.

Further discussion of ocean fertilization: The biomass of phytoplankton in the world's oceans amounts to only one to two percent of the total global plant carbon; yet these organisms fix between 30 to 50 billion tons of carbon (Gigatons C) annually, which is about 40 percent of the total fixed by all biota. (For reference, the atmosphere now contains 750 Gt C in the form of CO2.)

An uncontrolled experiment, the eruption of the volcano Pinatubo, provided an additional test and leads to estimates that can be used for planning a drawdown of atmospheric CO_2. The eruption injected crustal material, about three percent iron by weight, into the troposphere and lower stratosphere, allowing it to spread over the globe. Smaller particles may have been carried far enough to enhance productivity in distant regions, by far the largest of which is the Southern Ocean. Using estimates of the mass deposition flux there, Andrew Watson[31] figures that the iron deposited amounted to roughly 40,000 tons. (This amount is 100,000 times that used in the IronEx-II experiment.) Given a typical carbon/iron molar ratio of 105 for phytoplankton

[28] IPCC Working Group III 1996, Fig. 7.3, p. 254

[29] Sedjo, R.A. and A.M. Solomon. "Climate and forests." in *Greenhouse warming: Abatement and adaption.* N.J. Rosenberg, W.E. Easterling III, P.R. Crosson, and J. Darmstadter (eds.). Resources for the Future: Washington, D.C., 1989.

[30] Nordhaus, W.D. in IPCC WG-III

[31] Watson, A.J. "Volcanic iron, CO_2, ocean productivity and climate." *Nature*, 385, 587-588, 1997.

in iron-limited regions, this would enable additional new production, using up about 7x1013 mol of carbon. Such an increase would then release a pulse of the order of 1014 mol of oxygen into the atmosphere—which is consistent with changes in the hemispheric gradient of the O_2/N_2 ratio observed by R.F. Keeling et al.[32] Ocean fertilization could lead to significant drawdowns of atmospheric CO_2.

A simple calculation shows that a full-scale demonstration releasing 1 million tons (Mt) of iron in HNLC regions can tie up 20 Gt C, which would then be replenished from the atmosphere over some period of time. The drawdown of atmospheric CO_2 would depend on the rate of grazing by zooplankton and higher animals, i.e., on the effectiveness of the "biological CO_2 pump," which rapidly transfers carbon from surface waters to the ocean bottom. There was a slowdown observed in the rate of increase of atmospheric carbon dioxide following the Pinatubo eruption.[33] It is likely, therefore, that the atmospheric effect of the proposed demonstration would be measurable by existing CO_2 monitors.

Carrying out the operation would be relatively simple. Single-hulled supertankers exist in surplus; they are not suitable for carrying oil cargos but would be ideal for transporting ferrous sulfate, a waste product, and dispersing it—all at low cost. Patented formulations that slow the release of the iron would raise costs somewhat but greatly increase the efficiency of the iron absorption.

[32] Keeling, R.F., S.C. Piper, M. Heimann. "Global and hemispheric CO_2 sinks deduced from changes in atmospheric CO_2 concentration." *Nature*, 381, 218-221, 1996.
[33] Sarmiento, J.L. "Atmospheric CO_2 stalled." *Nature*, 365, 697-370, 1993.

ABOUT THE AUTHOR

Dr. Singer, professor (emeritus) of environmental sciences at the University of Virginia, is the founding president of the Fairfax-based Science & Environmental Policy Project. SEPP is a non-profit educational assocaiation of scientists concerned with providing a sound scientific base for environmental policies. Singer has held several academic and governmental positions, including as the first director of the U.S. Weather Satellite Service (now part of NOAA), deputy assistant administrator for policy of the Environmental Protection Agency, and most recently, chief scientist of the U.S. Department of Transportation. He devised the instrument used to measure stratospheric ozone from satellites and was first to point to and calculate the human-based

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