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This article was submitted to the  
National Academy of Engineering Symposium  
Washington, D.C.  
April 23 – 24, 2002

*U.S. Department of Energy*

Lawrence  
Livermore  
National  
Laboratory

**April 18, 2002**

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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

# ACTIVE CLIMATE STABILIZATION: Practical Physics-Based Approaches to Prevention of Climate Change\*

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## ABSTRACT

*We offer a case for active technical management of the radiative forcing of the temperatures of the Earth's fluid envelopes, rather than administrative management of atmospheric greenhouse gas inputs, in order to stabilize both the global- and time-averaged climate and its mesoscale features. We suggest that active management of radiative forcing entails negligible – indeed, likely strongly negative – economic costs and environmental impacts, and thus best complies with the pertinent mandate of the UN Framework Convention on Climate Change. We propose that such approaches be swiftly evaluated in sub-scale in the course of an intensive international program.*

**Introduction.** It's not generally realized that the Earth's seasonally-averaged climate is colder now than it's been 99% of the time since complex life on Earth got seriously underway with the Cambrian Explosion, 545 million years ago. Similarly, it's not widely appreciated that atmospheric concentrations of carbon dioxide – CO<sub>2</sub> – are only very loosely correlated with average climatic conditions over this extended interval of geologic time, in that it's been much colder with substantially higher air concentrations of CO<sub>2</sub> and also much warmer with substantially lower atmospheric levels of CO<sub>2</sub> than at present; indeed, the CO<sub>2</sub> level in the air is observed in the geologic record to be one of the weaker determinants of globally- and season-averaged temperature.

If, all of this thoughtfully considered, one wishes to maintain global climate at its current temperature-level – or at the somewhat higher value characterizing the Holocene Optimum several thousand years ago, or at that lower value of the Little Ice Age of three centuries ago, or at any other reasonable level – then purposeful modification of the basic radiative properties of the Earth – active management of the radiative forcing of the temperature profiles of the Earth's atmosphere and oceans by the Sun – is an obvious gambit. Indeed, it's likely the most overall practical approach to this particular issue.

The remainder of this presentation will be concerned with how best to effect – to actively manage – the desired changes in radiative forcing of the fluid envelopes of the Earth. “Best” will be determined from considerations of practicality, e.g., the economic efficiency commanded by the UN Framework Convention, as well as minimal interference with human activities, aesthetic considerations, collateral effects, etc. There is certainly no pretense that there is some absolute or utterly objective means of determining this practicality; rather, the range of examples given are merely illustrative of what might

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\* Prepared for invited presentation at the National Academy of Engineering Symposium *Complements to Kyoto: Technologies for Controlling CO<sub>2</sub> Emissions*, National Academy of Sciences, 2101 Constitution Avenue NW, Washington DC 20007, 23-24 April 2002. Research performed in part under the auspices of the U.S. Department of Energy under contract W-7405-eng-48 with the University of California, Lawrence Livermore National Laboratory. ***Opinions expressed herein are those of the authors only.***

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be accomplished in the very near term, how much it might cost, and what some of its more obvious ‘externalities’ might be. Detailed supporting information may be found in our earlier paper.<sup>1</sup>

**Radiative Budget Control.** It’s appropriate to note at the outset that basic concepts for purposeful modification of the Earth’s radiative properties certainly aren’t original with us; they were proposed at least as long ago as 1979 by Dyson and Marland<sup>2</sup> in the context of CO<sub>2</sub>-driven global warming, and perhaps most prominently by the National Academy of Sciences global change study group in 1992, which pointedly noted what appeared to them to be its surprisingly great practicality,<sup>3</sup> and the similar findings by the subsequent study by the Intergovernmental Working Group in 1995.<sup>4</sup> What we’ve done in our studies, set in the context of the UN Framework Convention’s Article 3,<sup>5</sup> is merely to mass- and cost-optimize previous schemes as well as to offer a few new ones, with a little attention given to how near-term studies of such optimized schemes for assuring climatic stability might commence.

The comparatively rudimentary atmospheric and oceanic circulation models currently used to predict climate variability with time variously predict increases in mean planetary temperature between ~1.5 and ~5 K, for doubling of atmospheric CO<sub>2</sub> concentration from the pre-industrial level of ~280 ppm to ~560 ppm (and associated changes in the mean concentrations of atmospheric water vapor, other greenhouse gases such as CH<sub>4</sub> and N<sub>2</sub>O and aerosols of various compositions and sizes, Earth-surface and -atmosphere reflectivity and radiative transport changes, etc.). Temperature changes of this magnitude-range would also be induced by a change in either solar heating or terrestrial radiative cooling of the order of 4 Watts/m<sup>2</sup> in the space- and time-average, which is of the order of 2%. Thus, if sunlight is to be preferentially scattered back into space, or the Earth induced to thermally radiate more net power, the characteristic surface area involved in changing net solar input by a space- and time-average of 4 Watt/m<sup>2</sup> is ~10<sup>-2</sup> A<sub>proj</sub> ~ 1.3 x 10<sup>16</sup> cm<sup>2</sup> ~ 1.3 x 10<sup>12</sup> m<sup>2</sup> ~ 1.3 x 10<sup>6</sup> km<sup>2</sup>, where A<sub>proj</sub> is the area which the solid Earth projects onto the plane perpendicular to the Earth-Sun axis; if a change is to be imposed uniformly over the entire Earth, it must be four times this size (i.e., the ratio of the Earth’s surface area to that of its disc).

Radiative budget control on the scales of present interest thus centers on generating and maintaining coverage of this 1-2% fraction of the Earth’s surface – or, alternately, its Sun-presented disc – with one or another materials which substantially modify the transport of either incoming sunlight (i.e., insolation) or outgoing thermal radiation emitted at-or-near the Earth’s surface over this area. If sunlight is blocked but terrestrial thermal radiation of ~20X greater wavelength is allowed to pass on out into space, then the Earth will cool by the desired amount – in the space- and time-average; conversely, if sunlight is allowed to pass through to the Earth’s surface, but terrestrial thermal radiation is blocked from escaping into space, then the Earth will warm by just the same amount – again, in the space- and time-average.

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<sup>1</sup> Teller E, Wood L and Hyde R, “Global Warming and Ice Ages: I. Prospects for Physics-Based Modulation of Global Change,” UCRL-JC-128715 (Univ. Calif. Lawrence Liv’r. Nat’l. Lab., August 1997). Also available as <http://www.llnl.gov/global-warm/>.

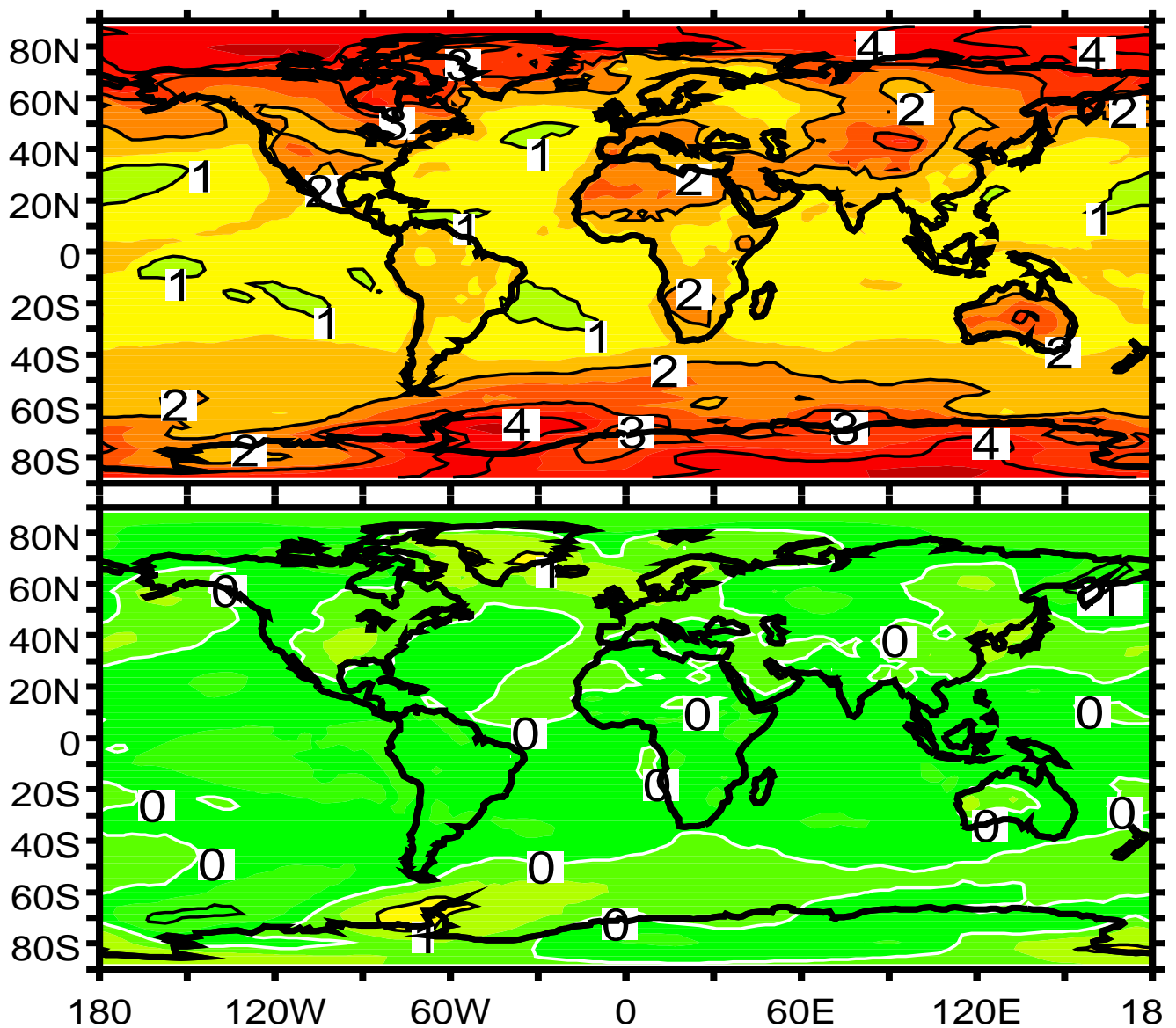
<sup>2</sup> Dyson FJ and Marland G., Technical Fixes for the climatic effects of CO<sub>2</sub>. *Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels*, USDoE Report CONF-770385 (USDoE, Washington DC, 1979).

<sup>3</sup> Panel on Policy Implications of Global Warming, “Policy Implications of Global Warming: Mitigation, Adaptation and the Science Base,” U.S. National Academy of Sciences (National Academy Press, Washington DC 1992).

<sup>4</sup> Working Group II, “Climate Change 1995 Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis,” Second Assessment Report of the Intergovernmental Panel on Climate Change, RT Watson, et al., eds. (Cambridge University Press, 1995).

<sup>5</sup> Section 3 of Article III of the United Nations Framework Convention on Climate Change states in part that “policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost.” This is often referred to as the Rio [Framework] Convention.

Before delving into the first-level details of some of the best ways in which to accomplish this, it's appropriate to point to the very important results of Govindasamy and Caldeira,<sup>6</sup> who have shown that such fractional removal of insolation uniformly over the entire surface of the Earth not only results in temperature changes of the predicted amounts in the space- and time-average, but *also* preserves the present climate in its seasonal and geographic detail, at least down through the mesoscales in space and time which are treated more-or-less aptly by present-day global circulation models. These most notable modeling results – which are quite contrary to previous hypotheses unsupported by modeling, but which have been confirmed by subsequent work – indicate that terrestrial climate may be stabilized by addition or subtraction of insolation along the lines that we propose not only “in the large” but *also* in the considerable spatial and temporal detail of interest to the man-on-the-street who experiences the highest-frequency components of climate as the daily weather in his micro-climate. Govindasamy and Caldeira also have offered a retrospectively plausible mechanistic explanation for why this remarkable set of results, shown in Figure 1 below, might have been expected.



<sup>6</sup> Govindasamy B and Caldeira K, “Geoengineering Earth’s radiation balance to mitigate CO<sub>2</sub>-induced climate change,” *Geophys. Res. Lett.* 27, #14, 2141 (2000); Govindasamy B, Caldeira K, and Duffy PB, “Geoengineering Earth’s radiation balance to mitigate change from a quadrupling of CO<sub>2</sub>,” *Global and Planetary Change* (in press).

**Figure 1.** The upper panel depicts the space- and time-averaged temperature change for a doubling of atmospheric CO<sub>2</sub> concentration from the pre-industrial baseline, in degrees Centigrade. The lower panel shows the same result, again for CO<sub>2</sub> concentration doubling accompanied by a 1.8% reduction in insolation; no significant temperature changes are seen. From Govindasamy and Caldeira.

**Ways-&-Means For Active Management Of Radiative Forcing.** ‘Covering’ of the order of 1 million km<sup>2</sup> of the Earth’s area with something that substantially affects the sunlight falling on it – or the Earth’s thermal re-radiation from it – might appear to be a rather ambitious task. However, since matter may be made to interact quite strongly with radiation, if its composition and geometry are properly chosen, the principal challenge is not the preparation or handling of the quantities of materials involved in this ‘cover’ but rather the ensuring that they will stay in place for usefully long intervals. [The average ‘thickness’ of scattering material over this ~10<sup>6</sup> km<sup>2</sup> is at most 10<sup>-4</sup> cm, so that the total volume is of the order of 10<sup>12</sup> cm<sup>3</sup> – that of a cube 100 meters on an edge – and the associated mass is ‘only’ of the order of 1 million tonnes.] As a specific example and looking ahead to one of our results, the present concern about global warming centers on the inputting of about 7 *billion* tonnes of carbon into the atmosphere each year and several times this level several decades hence; the annual deployment of barely 0.01% this mass of sulfur – roughly one ten-thousandth as much sulfur as carbon – in appropriate form and location can be made to entirely offset the “greenhouse effect” of the ten-thousand-fold greater mass of added CO<sub>2</sub>.

We have examined such considerations in a little detail, and the summary of our earlier results<sup>1</sup> is as follows. From a basic physics viewpoint, materials vary strongly in their ability to interact with and thus to manipulate optical-spectrum radiation, with resonant scatterers having the greatest mass-efficiency by far, good metals having about 10,000 times less specific radiative-interaction efficiency than resonant scatterers, and typical dielectrics having about 1% the specific radiative-interaction power as do the best metals. Each of these classes of materials offers distinct, independent, eminently practical ways-and-means of accomplishing the technical management of radiative forcing; some of these are old, but several of them are novel. We’ll briefly review a sampling of both old and new types.

Positioning of scatterers of incoming solar radiation in the Earth’s upper atmosphere – specifically, the middle to upper stratosphere – is a now-venerable approach that appears to provide the most practical deployment, as operational lifetimes of such engineered scatterers can be as long as a half-decade; required replacement rates are correspondingly modest. Thus, the stratosphere is where we propose to deploy all of the insolation-modulation scattering systems that we propose for near-term study.

Insolation-reducing means demonstrated twice in the past two decades – by the eruptions of El Chichon and Mt. Pinatubo, two large tropical volcanoes – and noted *per se* by the National Academy study illustrate the simplest of radiative forcing-management, albeit in a grossly non-optimized manner: Rayleigh scattering by aerosols of dielectric materials. Each of these volcanic events eruptively injected sufficient sulfate aerosol into the stratosphere to *decrease* temperatures in the Northern Hemisphere for 1-3 years by 10-30% as much as CO<sub>2</sub> in the year 2100 is variously predicted to *increase* these temperatures. Optimized formation and emplacement of sulfate aerosol is the most mass-costly – albeit a reasonably dollar-economical – means of scattering back out into space the sunlight fraction needed to offset the predicted effects of atmospheric CO<sub>2</sub> concentration in the year 2100. Interestingly enough, such Rayleigh scattering of sunlight, performed by stratospherically-deployed aerosols whose diameters are several-fold smaller than the wavelength of light itself, will selectively scatter back into space the largely deleterious ultraviolet component of sunlight while diminishing the light that we see – and that plants use for photosynthesis – only imperceptibly.

From the human perspective, skies would be bluer, twilights would be more visually spectacular, plants would be less stressed by UV photodamage and thus would be more productive, and children playing out-of-doors would be much less susceptible to sunburn (and thus to skin dysplasias and dermal cancers as adults), if this stratospheric Rayleigh scattering system were to be deployed. We've estimated the dollar-outlay cost of such active management of radiative forcing on the year-2100 scales to be about \$1 B/year, and no one to our knowledge has taken issue with this scoping-level estimate since we offered it a half-decade ago. Indeed, the National Academy study implicitly acknowledged the practicality of this type of approach, although it considered only thoroughly non-optimized dielectric aerosol scattering. Incidentally, such costs appear to be an order-of-magnitude less than health-care savings in the U.S. alone due to avoidance of UV skin damage – and far less than increased agricultural productivity due to avoidance of crop photodamage in the U.S. alone;<sup>7</sup> thus, the cost to the U.S. taxpayer of implementing this system of benefit to all humanity would appear to be quite negative: its economic benefits would greatly outweigh its economic costs.

As already noted, metals are greatly superior to dielectrics with respect to the specific efficiency with which they scatter radiation, and the several novel particular means which we've considered for the use of metals in management of radiative forcing indeed reflect a 10-100-fold mass savings, relative to dielectric aerosols. The geometries of metallic scatterers, as might be expected, center on metal dipoles and metallic screens, with dimensions selected to be comparable to the reduced wavelengths of the portion of the solar spectrum desired to be scattered. The physics of metallic scatterers – which, to be sure, also include small, thin metallic-walled superpressure balloons – suggest that they could most effectively scatter back into space the UV portions of solar insolation, just as do dielectric scatterers. These more highly engineered scatterers have significantly higher specific costs-to-emplac in the stratosphere than do dielectric aerosols, but their far lower masses result in estimated annual costs to address the reference year-2100 problem which may be as much as five times less than approaches of comparable power based on dielectrics: of the order of \$0.2 B/year.<sup>1</sup> Since they also would diminish the intensity of a portion of the solar spectrum which is net-damaging to both plants and animals, their 'side-effects' are comparably beneficial to those of dielectric aerosol Rayleigh scatterers; again, the net economic cost of deploying such a climate stabilization system would be substantially negative.

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<sup>7</sup> There are approximately 6,000 cases of fatal melanoma in the U.S. each year alone, most all of which are attributed to solar UV-B and -C exposure, along with approximately 1,000,000 cases of UV-B/-C-induced erythema (sunburn) so severe as to require professional medical treatment; a *per capita* cost of a melanoma fatality (medical care + economic loss-of-life) of \$500 K, plus a *per capita* (medical care + time-loss) case-cost of \$300 for severe sunburn, represents a loss to the U.S. economy of \$3.3 B/year; costs in the rest of the First World are probably at least this large, so that the world-wide annual cost due to photodamage to human skin is at least \$7 B/year. U.S. crops currently have a market value slightly less than \$100 B/year, and direct and indirect (due to UV-B and -C and to ozone, respectively) photodamage may be very conservatively estimated to be several percent (corresponding to a mean ground-level ozone concentration of 50-70 ppb), for a U.S.-only cost of several times \$1B/year; world-wide costs are likely to be at least 12 times larger, or several times \$12 B/year, as the U.S. accounts for less than 8% of global production of primary crops. Skin and crop photodamage thus likely amounts a substantial multiple of \$20 B annually, most of which could be avoided by scattering back into space from the stratosphere the majority of the incoming solar UV-B and -C irradiation, as well as the 'hard' or blue 'tail' of the UV-A spectrum.

In more recent work employing the IBIS terrestrial biosphere model in conjunction with the CCM3 Community Climate Model, Govindasamy, Caldeira and Duffy (*Global and Planetary Change*, in press) have modeling-estimated plant productivity changes associated with decreasing of insolation so as to just offset a doubled atmospheric concentration of CO<sub>2</sub> – and have found that it's substantially increased, essentially everywhere, mostly due to the fertilizing effects of doubled CO<sub>2</sub>, but also associated with less heat-related water-stress on plants. The corresponding large gain in plant productivity – a near-doubling, globally – has an estimated economic value of the order of \$1 T/year in its agricultural component alone – and, more importantly, implicitly provides a badly-needed margin of 21<sup>st</sup> century food production in the Third World. Credit for these huge additional benefits from active climate stabilization isn't taken in the estimate above of net economic impact of active climate stabilization.

Finally, resonant scatterers of sunlight offer huge gains in mass efficiency – although much of this gain seems likely to be lost in ‘packaging’ these materials so that they’re at once harmless and unharmed in the photoreactive stratosphere. Net, these novel materials appear to offer mass budgets a few-fold lower than the most interesting metallic scatterers but have operating costs comparable to dielectrics for the resulting radiative forcing management system. Once again, this novel type of climate stabilization probably would be aimed at attenuating the near-UV solar spectrum, and thus would have economic costs were would be net-negative.

Most all of these atmospherically-deployed scatterers remain ‘locked’ into the air mass-parcels into which they are initially deployed and thus eventually descend from the stratosphere, mostly as a result of vertical transport in the polar vortices at high latitudes. Once out of the stratosphere, they ‘rain out’ along with other tropospheric particulate material. The quantities so deposited are tiny compared to natural particulate depositions, e.g., wind-lofted dust and volcanic aerosol. The radiative forcing ‘magic’ results from the mid-stratospheric deployment of these optimally-formed scatterers. Virtually no natural particulate – with the exception of a small fraction of explosive volcanic ejecta – ever ascends so high, and thus is atmosphere-resident for so very long or ‘works’ so hard in a radiative transport sense; tropospheric particulates usually ‘wash out’ within time-frames of a few days to a couple of weeks. Even volcanic aerosol particulate typically is far too large to be mass-optimal, and also is loaded with chemical impurities which unfavorably impact stratospheric ozone levels; it’s of interest in the present discussion only as an undoubted proof-of-concept of the several different types of engineered-scatterer systems which we propose.

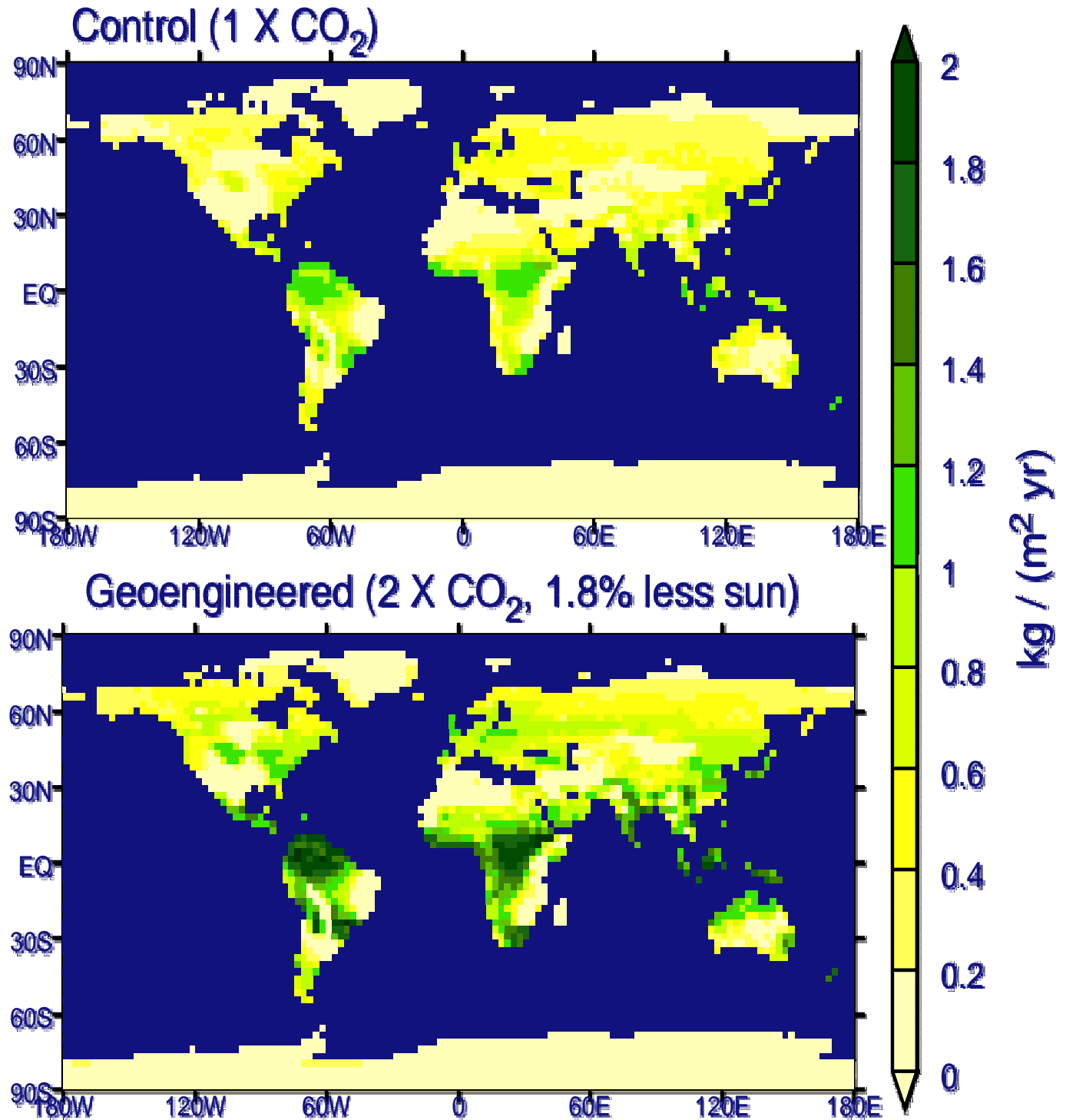
Finally, deployment of one or more metallic scattering screens so diaphanous as to be literally invisible to the human eye just inside of the interior Lagrange point of the Earth-Sun system and on the Earth-Sun axis represents the absolute optimum of all means known to us for insuring long-term climate stability, and is rather novel. Barely 3,000 tonnes of optimally-implemented metallic screen suffices to stabilize climate against worst-case greenhouse warming through preferential scattering of near-IR solar radiation so that it just barely misses the Earth, and the same-sized screen in a slightly off-axis position could be used to prevent future Ice Ages, as well, by scattering ‘near-miss’ solar radiation back onto the Earth. Exactly how to execute the deployment of such a long-term capital asset of the human race at the present time isn’t clear, however, and therefore its cost is indeterminate.

**Conclusions.** The foregoing considered, then, *if you’re inclined to subscribe to the Rio Framework Convention’s directive that mitigation of global warming should be effected in the “lowest possible cost” manner – whether or not you believe that the Earth is indeed warming significantly above-and-beyond natural rates, and whether or not you believe that human activities are largely responsible for such warming, and whether or not you believe that problems likely to have significant impacts only a century hence should be addressed with current technological ways-&-means rather than be deferred for obviating with more advanced means – then you will necessarily prefer active technical management of radiation forcing of the Earth to administrative management of greenhouse gas inputs to the Earth’s atmosphere, for the practical reasons sketched in the foregoing.*

Indeed, if credit is properly taken for improved agricultural productivity resulting from increased CO<sub>2</sub> and decreased solar UV fluxes – and human dermatological health benefits are likewise properly accounted for – we expect that the net economic “cost” of radiative forcing management will be seen to be extraordinarily negative, perhaps amounting to several hundred billions of dollars each year, world-wide, as suggested by the results shown in Figure 2. The more spectacular sunrises and sunsets and the bluer skies will be non-economic “collateral benefits.”



# Net Primary Productivity (NPP)



**Figure 2.** Net primary (plant) productivity of the terrestrial land-masses, as modeled by the IBIS code with slab ocean, used in conjunction with the Community Climate Model CCM3. The upper panel depicts the Earth with a pre-industrial atmospheric CO<sub>2</sub> concentration (280 ppm), while the lower panel depicts the Earth with a CO<sub>2</sub> concentration 2X that of the pre-industrial one and with 1.8% less insolation, as in Figure 1. The lower panel's globally-aggregated land-plant productivity is nearly twice that of the upper panel, which implies an agricultural crop value gain of the order of 1 trillion dollars/year for the enriched-CO<sub>2</sub> case. From Govindasamy, Caldeira and Duffy.

As noted above, active technical management of radiative forcing rather clearly will entail expenditures of no more than \$1 B/year, commencing not much sooner than a half-century hence, even in worst-case scenarios.<sup>8</sup> One thus might say, “Let’s just put a sinking-fund of \$1.7 B into the bank for use in generating \$1 B/year forever, commencing a half-century hence, and proceed with the human race’s business as usual. All of the Earth’s plants will be more productive for being much better-fed with CO<sub>2</sub> and much less exposed to solar UV radiation, kids can play in the sun without fear, and we’ll continue to enjoy today’s climate, bluer skies and better sunsets until the next Ice Age commences.” The economic counter-argument to this approach isn’t really obvious – and the ‘human impacts’ counter-arguments seem even more obscure. Though it’s not entirely self-evident, the ‘externalities’ of active technical management – including environmental costs – seem likely to be small in aggregate magnitude, on the basis of preliminary examinations through the present time.

We therefore conclude that technical management of radiative forcing of the Earth’s fluid envelopes, not administrative management of gaseous inputs to the atmosphere, is the path mandated by the pertinent provisions of the UN Framework Convention on Climate Change. Moreover, this appears to be true by a very large economic margin, one which may aggregate to not much less than a trillion dollars per year, world-wide, as it permits fertilization of the world’s crops by greater atmospheric CO<sub>2</sub> concentrations to occur without climatic regrets. One of the most pressing problems facing the human race in the 21<sup>st</sup> century – how to adequately feed the ~60% greater number of people demographically predicted to be alive a century hence – thereby begins to look distinctly manageable. Note in Figure 2 that the areas of greatest gain in land-plant productivity largely coincide with the areas of the planet in which the largest gains in human population are projected to occur. With active management of the radiative forcing of the atmosphere and oceans, humankind may be able to “air fertilize” its way around the basic food-production challenge of the 21<sup>st</sup> century, just as intensive use of soil fertilizers have bought humankind several decades of food-production grace in the last half of the 20<sup>th</sup> century.

We have tabled four distinct, independent sets of technical options for implementing active management of radiative forcing, three of which could commence operation essentially as soon as might be desired. These have been peer-reviewed in international conferences and *ad hoc* specialist workshops for a half-decade now. We thus suggest that the U.S. Government would be well-advised to launch immediately an intensive program to address all of the salient issues in active technical management of radiative forcing, including well-designed sub-scale experiments in the atmosphere. All such experiments, we point out, will terminate naturally back onto the present climatic posture, moreover on known, relatively short time-scales. Due to the obvious global impacts of *any* management scheme of any kind, the greatest feasible international participation in this program should be invited.

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<sup>8</sup> Assuming a time-averaged discount-rate of 5%, the present value of an eternal cash-stream of \$1 B/year commencing its flow a half-century hence is about \$1.74 B. This amount, put into the bank today at 5% interest, will grow to \$20 B by 2050, and that principal amount, in turn, will throw off the requisite \$1 B/year of radiative forcing management expenses until the end of time. This \$1.74 B of present-day “expense” for the “privilege” of continuing to enrich the atmosphere with CO<sub>2</sub> is equivalent to the amount of Federal gasoline tax collected every month or so. If one wishes to be conservative and assume that the ‘true,’ inflation-corrected long-term discount rate is only 3% and that full-scale mitigation of greenhouse gas inputs might have to be commenced as soon as a third-century hence, then one would need to deposit \$12.4 B in present dollars in order to fund the operation of the most expensive of the active radiative forcing management systems options at \$1 B/year (in 2002 dollars) for the rest of eternity, starting in 2035. This ‘eternal endowment’ amount for ‘perpetual care’ of the atmosphere is of the order of one year’s receipts of Federal gasoline taxes. A three-fold richer endowment would permit eternally-sponsored atmospheric management to commence a dozen years hence, in the event that the thermohaline circulation in the North Atlantic collapses within this time-frame, as some experts currently suggest may be happening.