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Global Warming and Ice Ages:

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GLOBAL WARMING AND ICE AGES:

I. Prospects For Physics-Based Modulation Of Global Change[*]

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ABSTRACT

It has been suggested that large-scale climate changes, mostly due to atmospheric injection of "greenhouse gases" connected with fossil-fired energy production, should be forestalled by internationally-agreed reductions in, e.g., electricity generation. The potential economic impacts of such limitations are obviously large: ≥$\$10^{11}$/year. We propose that for far smaller — <1% — costs, the mean thermal effects of "greenhouse gases" may be obviated in any of several distinct ways, some of them novel. These suggestions are all based on scatterers that prevent a small fraction of solar radiation from reaching all or part of the Earth. We propose research directed to quite near-term realization of one or more of these inexpensive approaches to cancel the effects of the "greenhouse gas" injection.

While the magnitude of the climatic impact of "greenhouse gases" is currently uncertain, the prospect of severe failure of the climate, for instance at the onset of the next Ice Age, is undeniable. The proposals in this paper may lead to quite practical methods to reduce or eliminate all climate failures.

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Introduction. In recent years, consideration of the possible warming of the climate due to the injection into the atmosphere of "greenhouse gases," particularly carbon dioxide, CO_2,[1] has motivated proposals to impose international limitations of the burning of fossil fuels, particularly ones yielding less heating-value per gram of CO_2 released, such as coal. The starting point of the present paper is the widely-appreciated fact[2] that increases in average world-wide temperature of the magnitude currently predicted can be canceled[3] by preventing about 1% of incoming solar radiation – insolation – from reaching the Earth.[4,5] This could be done by scattering into space from the vicinity of the Earth an appropriately small fraction of total insolation. If performed near-optimally,[6] we believe that the total cost of such an enhanced scattering operation would probably be at most $1 billion per year, an expenditure that is two orders of magnitude smaller in economic

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[1] Intergovernmental Panel on Climate Change, Climate Change 1995: The Science of Climate Change, JT Houghton, et al, eds. (Cambridge Univ. Press, Cambridge, 1996).

[2] E.g., Hansen JE and Lacis AA, Sun and dust versus greenhouse gases: An assessment of their relative roles in global climate change, *Nature* **346**, 713-9 (1990).

[3] See, e.g., MacCracken M, Geoengineering the Climate, Proceedings of the Workshop on the Engineering Response to Global Climate Change, Palm Coast FL, June 1-6, 1991, and UCRL-JC-108014 (1991), Lawrence Livermore National Laboratory, Livermore CA, 1991.

[4] Ref. 1, ibid. Also, Wigley, TML, "The Contribution From Emissions of Different Gases to the Enhanced Greenhouse Effect" in Climate Change and the Agenda for Research, T. Hanisch, ed. (Westview, Boulder, CO, 1994) estimates the present-day excess positive radiative forcing to be ~2 W/m^2, roughly three-fourths of which is due to CO_2 and one-quarter to CH_4.

[5] While it may be argued that uncertainties in the accuracy and fidelity of modeling tools are sufficiently great that they should not be relied upon to forecast reliably the effects of enhanced sunlight scattering on the climate [or as does, e.g., Lindzen RS, *Ann. Rev. Fluid Mech*. **26**, 353 (1994), that they are *fundamentally* unverified predictive tools], it is these same modeling tools – not the presently quite ambiguous observations of the actual climate – that are considered sufficiently robust to motivate the present level of concern about man-made climate change.

[6] One basic point-of-departure of the present paper from the large body of excellent previous work in similar directions [see, e.g., work surveyed in Panel on Policy Implications of Greenhouse Warming, Policy Implications of Greenhouse Warming: Mitigation, Adaptation and the Science Base, *U.S. National Academy of Sciences* (National Academy Press, Washington, DC, 1992) and in 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)] is the emphasis which we have placed on reducing deployed scattering system masses down to rather fundamental physical limits, consistent with contemporary engineering realities, in order to realize conceptual designs which may be the most practical to study in sub-scale and then to deploy in full-scale. We expect that all cost-effective mitigation efforts may require such optimization-focused design work. With respect to the fundamental utility of such efforts, we note that the section of the cited NAS report addressing "mitigation" options of the general type which we now consider concluded with the statement (on p. 460) "Perhaps one of the surprises of this analysis is the relatively low costs at which some of the geoengineering options [aimed at offsetting global warming] might be implemented."

terms than those underlying currently proposed limitations on fossil-fired energy production.[7,8,9] Some of these insolation-modulating scattering systems may be re-configured to effectively <u>increase</u> insolation by an amount – perhaps 3% – sufficient to prevent another Ice Age.[10]

We first survey various physical processes to accomplish this scattering. We then compare the various ways in which these scatterers may be deployed. Next, we propose that particular attention be given to three possible realizations of this technology-based program. We note geographical variability aspects of insolation modulation. We conclude by suggesting that the problem of possible changes in climate may be better solved by cooperative application of modern technologies rather than by international measures focused on prohibitions.

<u>Scattering Fundamentals.</u> In general, three basic types of scatterers exist, for scattering any type of electromagnetic radiation, including sunlight. The simplest type is based on any material in which the electric fields of light cause a displacement of electric charges; thus, any material at all can be used. The magnitude of the displacement of charges by an electric field of unit strength is measured by the dielectric constant ε, where $\varepsilon=1$ means there is no displacement. The scattering is proportional to $(\varepsilon-1)^2$, that is, highly polarizable materials generally will be more useful. This class of scatterer requires the near-optimal deployment[11] of an estimated several million tons of

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[7] See, e.g., testimony by Janet Yellen (Chair, Council of Economic Advisers to the President of the U.S.) before the House Commerce Subcommittee on Energy and Power, July 15, 1997, and press reports thereof (e.g., Fialka JJ, "Effort to Curb Global Warming Is Tied To Higher Energy Prices in Two Studies," <u>*Wall Street Journal*</u>, 16 July 1997, p. A2), in which estimates of ~40% increases in bulk fossil-energy prices in order to attain price-rationing of fossil fuel-derived energy sufficient to suppress greenhouse emissions below "dangerous levels" were characterized as "mid-level ones." These fractional price increases translate to ~$\$4\text{x}10^{11}$/year world-wide, or ~$\$10^{11}$/year in the U.S.

[8] All cost estimates in this paper should be regarded as scoping in character.

[9] We note that efforts directed to cost minimization of mitigation technologies is specifically supportive of the UN Framework Convention on Climate Change, whose Article 3 states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."

[10] 'A doubling of atmospheric CO_2 during the coming century is IGCC-estimated to result in a $2.5^{\pm}\,1.5^{o}$ C change in mean temperature, while the mean temperature decrease from the present level which prevailed at the middle of the last Ice Age is estimated to be ~10^{o} C.

[11] The large variance in previous estimates of the amount of dielectric scatterer required for full-scale insolation modulation appears to arise primarily from references to dimensionally non-optimized scattering materials, which can be quite mass-wasteful. (The optimal choice is to match the size of the scatterer to the reduced wavelength of the peak of the solar spectral radiance, and to maximize the squared difference from unity of the scatterer's dielectric constant divided by its specific gravity.)

scattering material in order to prevent an estimated (global- and time-)average temperature increase of 3±1.5˚C associated with a doubling of atmospheric CO_2 during the coming century;[12] the corresponding cost is ~$0.5 billion/year.

More effective scatterers can be realized by employing that subset of materials which exhibit high electrical conductivity. In this special case, electrons may be separated from their original locations by any distance, and it is the magnitude of the optical-frequency current carried by these electrons that characterize the effectiveness of such scattering materials – which are generally metals. Employed near-optimally, tens of thousands of tons of high-conductivity metal – roughly 1% of the required mass of dielectric materials – are required to scatter 1% of the Earth's total insolation; the corresponding costs are $0.07-0.14 billion/year.

In principle, the most effective of all possible scatterers are atoms or molecules that scatter light in resonance. Such extremely strong scattering can be obtained for light of a frequency adapted to a specific atom or molecule. The simplest example would be scattering of a narrow band of red light by lithium atoms or of yellow light by sodium atoms. Unfortunately, such exceptionally strong scatterings occur only in the immediate neighborhood of an atomic transition-frequency, and the atom will selectively interact with light of frequencies which deviates from the resonant one by about one part in ten million (for visible light). This difficulty can be overcome by broadening the resonance (accompanied by a proportionate weakening of the scattering-strength) or by using scatterers that have many separate resonances – or, most effectively, by a combination of these two approaches. Of the order of 1 million tons of such resonant-type scattering material are estimated to suffice to remove 1% of the total insolation of the Earth; the corresponding cost may be $0.3-0.75 billion/year.

The intrinsic scattering strengths of dielectrics, electrical conductors, and resonant scatterers are in the approximate ratio of 1 to 10^4 to 10^6, respectively,[13] for visible light; in practical implementations[14] useful for insolation modulation, however, these ratios may be much different.

Also, it is necessary to select scattering materials which scatter only with quite small losses, in order to minimize possibly undesirable heating of the portion of the atmosphere in which the scatterer is deployed.

[12] Intergovernmental Panel on Climate Change, Climate Change 1995: The Science of Climate Change, JT Houghton, et al, eds. (Cambridge Univ. Press, Cambridge, 1996).

[13] In evaluating the mass efficiency of any *scattering unit* or a *scattering system*, consideration of the space- and time-averaged optical-frequency current density in the matter comprising the system gives a general-purpose figure-of-merit for the mass budget of the system. When multiplied by the ‘optical leverage’ figure-of-merit, it generates an index of effectiveness of mass utilization in creating a sunlight-deflecting system. Note

<u>How Should Scatterers Be Deployed?</u> There are three obvious choices for deployment-sites for scatterers on scales of interest for insolation modulation.[15] One is the terrestrial stratosphere, the second is in a low-Earth orbit (i.e., an orbit whose radius may be as much as twice the radius of the Earth), and the third is a position along the line between the centers of the Earth and the Sun (approximately one hundred times the Earth's radius distant from the Earth).

Of the three deployments, the stratospheric location is by far the least expensive on a pound-for-pound basis; positioning mass in the stratosphere currently is at least 10^{4} times less costly than putting it into low Earth orbit.[16] Moreover, the mid-stratospheric residence time of sub-

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that this average (optical-frequency) current density-per-gram metric permits the comparison of metallic, dielectric and atomic-resonant scattering materials, moreover in a manner independent of particular scattering system geometry. It merely looks at <u>the</u> quantity which scatters the sunlight's optical field: the space- and time-averaged current density driven up by the electric fields of the solar photons in the matter constituting the *scattering unit*, and the outgoing-wave optical-frequency fields which this density generates.

Most dielectric materials of interest have optical dielectric coefficients $\varepsilon \leq 2$, and we generally must consider $(\varepsilon-1) \leq 9\text{x}10^{-13}$ farads/cm. Available metals (e.g., Al) have electrical resistivities $\geq 3\text{x}10^{-6}$ ohm-cm (taking some degradation from best bulk properties for very thin layers), i.e., conductivities $\sigma \leq 3\text{x}10^{5}$ mho/cm. Optical frequencies of resonant transitions are ~10^{15} Hz, and these transitions correspond to electron travel over orbital distances ~3 Å, i.e., across atoms of ~3 Å diameter. Take a reference mid-visible optical angular frequency of ~$4\text{x}10^{15}$ sec^{-1}. Then the optical current density I in a unit volume (whose greatest dimension is assumed to be $\leq \lambda/2\pi$) of such a dielectric at unit electric field strength is $I \sim E/Z \sim \omega C$, or $4\text{x}10^{15}$ x $9\text{x}10^{-13}$, or $3.6\text{x}10^{3}$ amp/cm^{2}. The current density in the same circumstances in a good metal is just $I \sim \sigma E \sim \sigma$, or $3\text{x}10^{5}$ amps/cm^{2}. Unit optical electric field strength of 1 V/cm corresponds to an optical flux of 10^{-4} W/cm^{2}, so that sunlight's intensity at 1 AU of 0.1 W/cm^{2} implies a mean frequency-averaged optical electric field of ~30 V/cm. This optical field strength will drive ~30 transitions/sec in a typical full-strength-dipole atomic oscillator, as noted above; unit optical electric field strength thus will drive ~$3\text{x}10^{-2}$ transitions/second in such an atom. Each atom is assumed to occupy a volume of ~$3\text{x}10^{-23}$ cm^{3}, so that ~10^{21} transitions/sec are driven by a unit-strength solar-spectral optical electric field in a cm^{3} volume of such material. Each such transition corresponds to a optical-frequency current of a single electron's charge – $1.6\text{x}10^{-19}$ coulombs – moving through a distance ~$3\text{x}10^{-8}$ cm every ~10^{-15} sec. This corresponds to a optical frequency current density of ~$5\text{x}10^{9}$ amp/cm^{2} (!).

For constituting *scattering units*, then, the relative figures-of-merit of best-available dielectrics, metals and resonant-scatterers are roughly $1:10^{2}:10^{6}$.

[14] The "packaging mass overhead" for quasi-resonant scatterers typically is much larger than that for metallic and dielectric scatterers, so that much of the former's huge intrinsic mass advantage is lost in scattering systems prepared for multi-year durability-in-service.

[15] The Earth's surface is not considered for reasons of land-use and local microclimate impacts, while the ocean surface poses stability/durability/navigation compatibility concerns, and tropospheric residence times are not usefully long for the types of scattering systems which we consider.

[16] We estimate a total cost of lifting mass into the stratosphere on wide-body commercial aircraft to be ~$0.3/pound, whereas the current cost of putting a pound-mass of payload into low Earth orbit by

microscopic scattering particles of anthropogenic[17] and natural[18] origins is comparable to the half-decade residence time of its molecular components,[19] so that appropriately fine-scale particulate loadings of the middle stratosphere will persist for five-year intervals. However, the stratosphere is a chemically uncongenial location due to the high flux of ultraviolet radiation from the Sun and the presence of oxygen, particularly in the more reactive form of ozone.

Ideally, we would prefer to deploy scattering systems – or their principal components – that would remain in place and retain their performance-pertinent properties for a century, which is of the order of the interval[20] required for a CO_2 emission pulse to be effectively sunk into the deep ocean. However, we consider the half-decade mid-stratosphere residence time to be sufficiently long for practical deployments. We may re-constitute the deployment of a scattering system twice per decade (or 20% per year), and we even consider such a short duration to constitute a relatively rapid, naturally-operating means of disposing of possible unwanted side-effects of insolation modulation. Chemical stability in the stratosphere, even for material with readily available electrons on its surface, is a tractable issue for present purposes.

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contract with commercial space-launch services is ~$5,000, for 5-15 ton payloads. Indeed, some types of stratospheric deployment of oxide particulates – e.g., SO_2 or Al_2O_3 – might be accomplished simply by operating one or more well-engineered combustors – e.g., of elemental S or Al – at high-altitude, near-equatorial ground-sites, from which stratospheric injection of warm gas is intrinsically advantaged. (Combustor engineering would focus on mass-efficient, optimal-sized scatterer particle generation in the vertically-directed exhaust, which likely would have a rocket nozzle character in order to facilitate swift manipulation of the temperature and density of combustion products across usefully large ranges.)

[17] Feely HW and Spar J, Tungsten-185 From Nuclear Bomb Tests As a Tracer For Stratospheric Meteorology, *Nature* **188**,1062-4 (1960); Telegadas K and List RJ, Atmospheric Radioactivity along the HASL Ground-Level Sampling Network, 1968 to mid-70, as an Indicator of Tropospheric and Stratospheric Sources, *J. Geophys. Res.* **74**, 1339(1969); Telegadas K, Report 243 (U.S. Atomic Energy Commission, Washington, DC, 1971);

[18] Trepte CR and Hitchman MH, Tropical stratospheric circulation deduced from satellite aerosol data, *Nature* **355**, 626-8 (1992); Trepte CR, Veiga RE, and McCormick MP, The Poleward Dispersal of Mount Pinatubo Volcanic Aerosol, *J. Geophys. Res.* **98**, 18563-73 (1993); Grant WB et al, Use of volcanic aerosols to study the tropical stratospheric reservoir, *J. Geophys. Res.* **101**, 3973-88 (1996).

[19] Boering KA, Wofsy SC, Daube BC et al, Stratospheric Mean Ages and Transport Rates from Observations of Carbon Dioxide and Nitrous Oxide, *Science* **274**, 1340-3 (1996).

[20] See, e.g., Manabe S and Stouffer RJ, Century-scale effects of increased atmospheric CO_2 on the ocean-atmosphere system, Nature **364**, 215-7 (1993).

Deployment in low-Earth orbit is an obvious alternative,[21] one which offers potentially very long-term positional stability combined with excellent durability of many materials. Technologies that could greatly decrease the cost of space-launch could make a telling difference in the practicality of all types of space-deployed scattering systems of scales appropriate to insolation modulation.[22] Light pressure arising from the momentum imparted to the scatterer by sunlight may significantly perturb the orbital elements of the scatterer, and managing this momentum poses an additional technical challenge to LEO-deployed scatterers.

An interesting though not necessarily a practical case comprises the third alternative.[23] Terrestrial insolation has an angular definition of one part in 120. Thus, if the scattering system is deployed $\sim 10^2$ times the Earth's diameter distant from the Earth, small-angle ($\leq 1^\circ$) scattering will suffice for an appropriate deflection of the Earth-directed sunlight (either toward the Earth, if warming is desired, or away from it, if cooling is sought). This small angle permits the use of relatively very modest quantities of either conductors or dielectrics to comprise the scattering system – approximately 10^2-fold smaller than those needed to effect insolation modulation of the same magnitude when deployed near the Earth.[24] The management of the radial and angular momenta of

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[21] National Academy of Sciences, National Academy of Engineering and Institute of Medicine, Policy Implication of Greenhouse Warming: Mitigation, Adaptation, and the Science Base (National Academy Press, Washington, D.C., 1992).

[22] Since space-deployed scatterers could in principle last indefinitely, they have a several dozen-fold advantage in time-integrated mass budget relative to stratospherically-deployed ones, which must be re-constituted twice per decade. This durability-in-service saving trades off interestingly, albeit not compellingly, against the present $\sim 10^4$-fold disadvantage in cost of transportation to deployment-site. Space-launch service costs will have to decrease to a few dozen dollars per pound in order to become competitive for present purposes. High-acceleration payload launchers are potentially of interest, as scatterer payloads are likely to be very acceleration-tolerant – and perhaps can be segmented into quite modest sizes and masses, as well.

[23] Positioning a sunlight-*shade* or Snell's Law-*refractor* (i.e., a 1-D Fresnel phase plate) composed of 10^{14} gms of lunar glass near the Earth-Sun interior Lagrange point (L1) has been suggested in Early JT, Space-Based Solar Shield To Offset Greenhouse Effect, *J. Brit. Interplanet. Soc.*, **42**, 567-9 (1989). The present proposal positions a metallic *small-angle-scatterer* of sunlight of comparable area but $\sim 10^5$-fold smaller mass Sunward of L1. A system of this type likely would be assembled quite close to the Earth, e.g., in LEO, and then rapidly "flown" into its deployment location as a solar sail, exploiting its very small mass-to-optical cross-section and its active radiation momentum management capabilities.

[24] The total areal size of such a *scattering system* must remain the same as *scattering systems* deployed in close proximity to the Earth, but its total mass potentially may be much more modest, as it must scatter sunlight only through $\sim 10^2$-fold smaller angles. In particular, the conducting elements of the *scattering units* need carry only $\sim 10^2$-fold smaller currents, so that they can be of 10^2-fold smaller cross-sectional area (for a given optical electric field strength, which is effectively constant for all *scattering system* deployments in ~1 AU sunlight), and thus can have 10^2-fold smaller mass. The mass of such a *scattering system* can be estimated by noting that

the sunlight scattered poses basic, albeit quite tractable, issues with respect to position maintenance.[25]

Some Specific Proposals. There are obviously numerous ways in which the potentialities and difficulties mentioned above can give rise to a workable scattering system, one of a scale adequate

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the total area must be ~1% of the Earth's disc, while it must have good metallic conductors of ~3 x10^{-11} cm^2 cross-sectional area (~600 Å thick by ~1000 Å in transverse width) spaced every $100\lambda/2$~3 x 10^{-3} cm in both transverse dimensions. If the density of the conductor is taken to be 3 gm/cm^3 (e.g., Al), then the mass density is ~ 1.2x10^{-7} gm/cm^2, and the total mass is just this density times the 1% of the Earth's disc area of ~1.2x10^{18} cm^2 which is to be sun-shaded, or ~1.2x10^{16} cm^2: ~1.4x10^9 gms. The total mass of the ideal *scattering system* thus is ~1.5x10^9 gm or 1,500 ton – plus whatever overhead mass is required to deploy and operate these (literally) diaphanous scattering screens; the actual *scattering system* has about twice this mass – ~3400 tons – for reasons which are discussed below.

The possibilities of incrementing or decrementing terrestrial insolation in manners which are both geographically and spectrally selective by use of such a distant scattering system seem obvious.

[25] The momentum carried by sunlight, while very small, is assuredly not negligible: at 1 AU, it amounts to ~4x10^{-5} dynes/cm^2. Over a day, this accumulates to ~3 dyne-sec/cm^2 and, over a year, to ~10^3 dyne-sec/cm^2 of impulse fluence. If exactly backscattered (toward the sun), only radial momentum is gained by the *scattering unit*; however, if deflected at any angle $<\pi$, it will also impart angular momentum to the scatterer: the Poynting-Robertson effect. Since *scattering units* typically have an areal mass <<10^{-3} gm/cm^2, they can undergo many gee-sec of acceleration even during a day, and thousands of gee-second annually (i.e., can see Δv of >>10 km/sec). Such velocity changes in essentially all orbits of interest are almost invariably intolerable, and either *deployment* or *operational* means must be devised to avoid them.

Unwanted angular momentum may be readily jettisoned by time-varying the orientation of a relatively very small reflector capable of scattering sunlight through a high mean angle. However, the radial momentum imparted by sunlight must be sustained for intervals as long as a half-year, until the Earth's orbital motion about the sun will dissipate it; in most cases-of-interest, this is a very long time-interval over which to tolerate radial momentum absorption. However, if the *scattering unit* is deployed sunward of the Earth's orbit but quasi-orbits the sun at the same angular rate as does the Earth (so as to continually shadow-shield the designated fraction of the Earth), then it may in principle sink as large fraction as may be desired of the incident sunlight's radial momentum into the solar gravitational field, i.e., it may position itself closer to the Sun than the L1 point so as to sink the scattered radiation's radial momentum into the solar gravitational field; the smaller its areal mass density, the more Sunward of L1 it must position itself. Now the radial radiation momentum flux is ~4x10^{-5} dynes/cm^2, only 5x10^{-5} of which is deposited on the scatterer as it deflects the incident sunlight by 10^{-2} rad, so that the mass density corresponding to deposited radiation radial momentum balancing the gravitational 'deficiency' is ~1.5x10^{-7} gm/cm^2. This is only a few times greater than the areal mass density of the ideal scattering system positioned at L1. Thus, by moving ~1% inward from L1 – and increasing the total area of the scattering system by ~2-fold, in order to continue to shadow the Earth while moving further Sunward from it, we can simultaneously sink the residual radial momentum of the scattered sunlight into the solar gravitational field and maintain the desired shading of the Earth.

Residuals in both radial and angular momentum flux from solar gravitation and from the Poynting-Robertson effect, respectively, are probably best sunk by sunlight retroreflection action performed by a relatively small area (i.e., 0.3%) of high-angle reflector. However, this necessarily will have a ~50X greater areal mass-density than does the small-angle-scattering screens of greatest interest, so that a ~15% overhead cost is thereby incurred by the *scattering system*.

to modulate the total insolation of the Earth by 1%. In the following, we shall provide some details regarding specific possibilities, ones selected to illustrate basic features of each of the major classes of scattering systems.

Sub-Microscopic Oxide Particulates. During the present decade, the eruption of Mt. Pinatubo in the Philippines induced a transient drop in the global mean temperature of ~0.5° K, apparently due to insolation modulation by volcanic particulates.[26] It is believed that this cooling was induced predominantly by scattering of sunlight by SO_2-based particulates of sub-micron scale, ones which may have grown into more effective scatterers by scavenging residual stratospheric water and cations, resulting in myriad still-sub-micron droplets of high-concentration sulfur acids and salts. Indeed, it has been suggested that the advent of marked greenhouse effects due to CO_2 emissions has been delayed through the present time by the simultaneous emission of large quantities of sulfate particulates (primarily arising from the ~2±1% sulfur content by weight of typical fuel-grade coal), resulting in significant tropospheric scattering of sunlight.[27] To these extents, the case of dielectric scattering-based insolation modulation already has some empirical basis.

It may well be feasible to transport and disperse enough SO_2 (or SO_3 or H_2SO_4) into the stratosphere to produce the desired insolation modulation effect[28,29] – and even to do so partly on the

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[26] Trepte CR and Hitchman MH, Tropical stratospheric circulation deduced from satellite aerosol data, *Nature* **355**, 626-8 (1992); Trepte CR, Veiga RE, and McCormick MP, The Poleward Dispersal of Mount Pinatubo Volcanic Aerosol, *J. Geophys. Res.* **98**, 18563-73 (1993); Grant WB et al, Use of volcanic aerosols to study the tropical stratospheric reservoir, *J. Geophys. Res.* **101**, 3973-88 (1996).

[27] See, e.g., Taylor KE and Penner JE, Response of the climate system to atmospheric aerosols and greenhouse gases, *Nature* **369**, 734-7 (1994); Chuang CC, et al, An Assessment of the Radiative Effects of Anthropogenic Sulfate, *J. Geophys. Res*. **102**, 3761-78 (1997); and Intergovernmental Panel on Climate Change, Climate Change 1995: The Science of Climate Change, JT Houghton, et al, eds. (Cambridge Univ. Press, Cambridge, 1996).

[28] See, e.g., Dyson FJ and Marland G, Technical fixes for the climatic effects of CO_2. *Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels*. USDoE Report CONF-770385 (USDoE, Washington DC, 1979); Budyko MI, The Earth's Climate: Past and Future. (Academic Press, New York, 1982); Broecker WS, How to Build a Habitable Planet (Eldigio Press, Palisades, NY, 1985).

[29] In this approach, advantage is taken of the stronger Rayleigh scattering of the shorter wavelengths of optical sunlight as compared to those of terrestrial thermal emissions. A performance-optimized *scattering system* of present interest consists of a world-wide, ultra-thin cloud of dielectric particles, each of 0.05-0.1 μm diameter, deployed in the Earth's stratosphere. The Rayleigh scattering cross-section Σ of a particle of volume V whose polarizability $\alpha=3(\varepsilon-1)/4\pi(\varepsilon+2)$ for photons of angular frequency ω is $\Sigma = (8\pi/3)(\omega/c)^4\alpha^2V^2$. [See, e.g., Landau LD and Lifshitz EM, Electrodynamics of Continuous Media (Pergamon, Oxford, 1984).] For such a spherical particle whose diameter is equal to a quarter-wavelength of 0.5 μm radiation which has a dielectric coefficient ε~1.7 (e.g., a water-rich microdrop of refractive index ~1.3), Σ may be estimated to be ~$5x10^{-12}$

basis of existing experience, as well as much prior analysis. It has also been suggested that alumina injected into the stratosphere by the exhaust of solid-rocket motors might scatter non-negligible amounts of sunlight.[30] We expect that introduction of scattering-optimized alumina particles into the stratosphere may well be overall competitive with use of sulfur oxides;[31] alumina particles offer a distinctly different environmental impact profile.

Conducting Sheets. The reference 1% reduction in insolation might be obtained by deploying electrically-conducting sheeting, either in the stratosphere or in low Earth orbit. Three quite different physical mechanisms comprise the foundations of the three distinct approaches which we consider. In the first, mixtures of suitable metals are deposited in ultra-thin layers and convenient area, and are then protectively coated.[32] Platelets of such material are then deployed in

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cm^2. Thus, $\sim 10^{28}$ of these particles, uniformly distributed in the stratosphere, would be required to scatter-shield the 5×10^{18} cm^2 of terrestrial surface with optical density 10^{-2} at the sub-solar point. (While only the bluer portion of the visible spectrum, $\lambda \leq 0.5$ μm, would be scattered with this cross-section, the effective scattering in the earlier half of local morning and the latter half of local afternoon in the tropics and all day at higher latitudes is considerably greater than this value, due to the greater atmospheric path traversed by incident sunlight, so that the net required energetic effect of panchromatic scattering is attained, in first approximation). Each of these scattering particles may be estimated to have an average mass of $\sim 10^{-15}$ gm (i.e., be ~0.12 μm in diameter and of unit density), so that the required quantity of them would imply a total mass of the *scattering system* of $\sim 10^{13}$ gms, or 10,000,000 tons. A mean stratospheric lifetime of each scattering particle of 5 years would imply a required injection rate of 2×10^6 tons annually, or a time-averaged injection rate of 60 kg/second, which is feasible to maintain e.g., with highly parallel exercising of existing fine-aerosol-dispersion technology.

[30] E.g., Brady BB, Fournier EW, Martin LR and Cohen RB, Stratospheric Ozone Reactive Chemicals Generated by Space Launches Worldwide. *Aerospace Report No. TS-94(4231)-6*. (The Aerospace Corporation, El Segundo, CA, 1994).

[31] Because of the strong dependence of the Rayleigh scattering cross-section on ε, $[(\varepsilon-1)/(\varepsilon+2)]^2$, when ε is not much greater than unity, it would be more somewhat mass-efficient to deploy alumina microspheres, instead of $SO_2/SO_3/H_2SO_4$ ones: the significantly greater density of alumina (~ 3.5 gm/cm^3) is more than compensated by its greater dielectric coefficient, 3.10. (Alumina, like sulfate, is ubiquitous in the terrestrial biosphere, and its stratospheric injection seemingly poses no significant environment issues. However, its refractory character makes it more challenging to deploy, at least in some modes. A notable exception might be a high-average-power combustor of aluminum powder deployed at a high-altitude, near-equatorial ground-site, one whose carefully-engineered exhaust-stream could hydrodynamically penetrate the overlying tropopause and inject ≤0.1 μm-diameter alumina particles into the mid-stratosphere with high mass-efficiency.) Worth noting in passing is the fact that the annual tonnages of either sulfur or aluminum oxides presently proposed for stratospheric deployment are tiny compared to the quantities of these materials which are either naturally lofted into the atmosphere (e.g., by dust storms) or are already injected by human activities (e.g., burning of fossil fuels of all types).

[32] Absorption of solar photons with thermal (quasi-isotropic) re-radiation of the absorbed energy may be reasonably mass-efficient in some circumstances, e.g., when using photoelectric-effect (bound-free) absorbers. For instance, the photoelectric cross-section of good metals just above the work-function-edge for near-optical radiation is $\sim 3 \times 10^{-17}$ cm^2, and is $\sim 3 \times 10^{-18}$ cm^2 at three times this photon energy (i.e., a 10^7- and 10^8-fold reduction below the line-center bound-bound resonant cross-section, corresponding to the relative final-state

the stratosphere – or perhaps in low Earth orbit – and act to absorb sunlight by the photoelectric effect; the absorbed energy is then thermally re-radiated, with ~half escaping into space. In the second, metallic "nets" of ultra-fine mesh-spacing are employed to reflect solar photons of optical wavelengths into space.[33] In the third, optimized metallic-walled balloons – similar in concept to ones with which children play – are self-deployed into the stratosphere from ground level, where they serve to scatter insolation.[34] Each of these approaches involves total masses of the order of

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phase-space volumes of the two types of transitions). For *scattering unit* design purposes, an effective photoelectric cross-section of 10^{-17} cm^2 is a reasonable estimate (taking into account finite solar spectral width requirements and considering that the solar spectral intensity falls rapidly above even the lowest-energy single-element photo-edge, that of Cs metal at a photon wavelength ~0.37 μm), and assuming that all photons with energies above the photo-edge interact with this cross-section. Likewise, note that a multiple alkali-metal alloy system can lower this photoedge to an effective 2 eV threshold (e.g., as the tri- and quad-alkali-metal-alloy photocathodes of commercial photodetection devices routinely do). A sheet of this material of a few dozen atoms thicknesses – ~100 Å – would then represent an extinction length for blue-green photons, and would have a mass-density of ≤3x10^{-6} gm/cm^2. Then, assuming that *scattering units* comprised of such 10^{-6} cm-thick sheeting would absorb half the incident solar spectrum and that the corresponding scattering system would sun-shield 0.01 of the Earth's disc continuously, the minimum mass-budget of an efficiently implemented *scattering system* comprised of such ultra-thin sheets of photoelectric absorber/thermal re-radiator would be (2)(10^{-2})(1.2x10^{18} cm^2)(3x10^{-6} gm/cm^2)~7x10^{10} gms ~ 70,000 tons. If deployed either in the atmosphere or in LEO, individual *scattering units* could be effective only ≤50% of the time, so that ≥140,000 tons would be required to fully implement such a *scattering system*.

The constituent materials of every efficient photoelectric absorber for solar-spectrum radiation inherently are readily oxidizable, particularly in the highly (photo)reactive upper atmosphere, so that only LEO deployment of such systems appears feasible – unless ≥two-fold mass penalties are paid for protective jacketing, e.g., SiO_2. In addition to having a relatively large mass budget for a space-deployed system, such an absorption/re-radiation module in space would have the active momentum-management requirements characteristic of any space-based *scattering system*; this additional complexity would trade off against the multi-decade lifetimes (and thus far lower annualized costs) implicit in LEO deployment.

[33] The scattering system of this approach is comprised of a set of single-layer screens which scatter incident sunlight through ~π/2 rad, and whose conducting elements must be ~1 skin-depth in longitudinal extent, or ≥200 Å, by ~300 Å in transverse width, spaced at ≤3x10^{-5} cm distances in both dimensions; packaging mass for protection against stratospheric oxidation would be comparatively small, if metal having a thin protective oxide, such as Al, is used. Such a high-angle *scattering system* would have electrically conducting 'wire' elements massing a total of ~15,000 tons; averaging random orientation and diurnal availabilities drives this up by ~2π, to ~90,000 tons. (Overhead mass for deployment and operation would, of course, be additional, although, in fractional terms, it would be smaller, as the scattering screens would be much stronger, due to their thicker conducting members.)

[34] Thin-walled helium-filled balloons are routinely employed to lift multi-ton payloads to 30-50 km altitudes, and maintain them there for multi-day intervals (limited mostly by the durability-against-photooxidation of the balloon's plastic wall). It thus seems entirely reasonable to consider ultra-thin metallic-walled balloons, partially inflated with a suitable lifting-gas, e.g., H_2, as sunlight-backscattering 'stratostats', for they can be expected to have very long stratosphere residence times (probably limited by micrometeoritic puncture-rates). A wall thickness of ~0.02 μm of e.g., Al, is ~1 skin-depth at the 8x10^{14} Hz frequencies characteristic of mid-visible solar radiation and thus suffices to (predominantly) backscatter the blue end of the incident solar spectrum; however, it is ≤0.2 skin-depth at 2-3x10^{13} Hz and thus is nearly transparent to Earth thermal emissions in the 8-14 μm wavelength atmospheric pass-band. Each of these balloons thus constitutes a 'micro anti-greenhouse': it passes space-directed low-frequency photons emitted by the Earth but reflectively backscatters-into-space the high-frequency ones incoming from the Sun.

10^5 tons, although the detailed mass budgets are quite different. The total cost-to-own any one of these three metallic systems at full-scale appears to lie in the range of \$0.07-0.14 billion/year.

Since the thickness of the balloon's metallic wall is determined by electrodynamic skin-depth considerations, the balloon diameter is selected so as to position it at the desired stratospheric altitude when it is fully expanded, subject to the constraint that it must be buoyant at the launch-site altitude. An Al wall thickness of 0.02 μm, a balloon radius of 4 mm, a fully-inflated volume of 0.25 cm^3, a mass of 10^{-5} grams and an optical scattering cross-section (between ~0.25 and ~1 μm wavelength) of 0.5 cm^2 correspond to a balloon deployment altitude of 25 km. (Likely different choices of deployment altitude involve ≤2-fold adjustment of the balloon diameter while keeping its wall thickness invariant.) Since it is required to scatter-shield ~$5x10^{16}$ cm^2 (recalling that 1% of the Earth’s <u>total</u> area is to be so sun-shielded), ~10^{17} of these ‘‘self-lofting blue-UV chaff’’ objects will be required, with an associated mass of ~10^{12} grams, or 1,000,000 tons. If they are deployed uniformly over a 50 year interval (i.e., quickly compared to a doubling-time of atmospheric CO_2), then ~$2x10^{10}$ grams/year – ~$6x10^7$ balloons/sec, or 10^8 cm^2/sec, or 1 hectare/sec of these scatterers – must be created and deployed. (Newspaper printing-press technology seems a particularly likely basis for ‘printing’ these balloons on a H_2-loaded Al bilayer-sandwich substrate. High-circulation major newspapers print ~10^6 copies of a ~10^{-2} hectare-area newspaper daily, for a round-the-clock mean rate of ~0.1 hectare printed per second; the peak printing rate is ~0.3 hectare/sec. Thus, the time-averaged balloon creation-and-deployment rate is comparable to the peak output rate of a large newspaper printing-facility.) This deployment rate will require $4.5x10^7$ lbs/year of Al-as-foil (at a current annual cost of ≤\$40 M for ingot, likely a few times this for mass-produced ultra-thin foil), and a ~15-fold lower mass of several-fold cheaper H_2 gas: ~1,500 tons.

These ‘‘self-lofting blue-UV chaff’’ balloons constitute one of the lowest-technology approaches, in that, once created and released at ground-level, they self-*deploy* and automatically-*operate*. The feedstream requirement is only ~1% of the current total annual production of aluminum metal. Since 6% (by mass) of the Earth’s crust is Al, the quantity of ultra-thin Al foil drifting down from the skies during the mid-21st century wouldn’t discernibly impact the environment, the more so as such very thin foils would photooxidize to the hydrated oxide quite rapidly in the wet troposphere: at ~290^{o}K, Al exposed to dry oxygen forms a stable oxide layer of 10-30 Å thickness, but wet oxidizing atmospheres can form >1 μm hydrated oxide layers on bulk Al in a matter of hours – and hydrated AlO_x films crumble to powder very rapidly. (It therefore should be feasible to deploy such ‘‘self-lofting blue-UV chaff’’ from desert sited-factories – or from high-latitude ground-sites – and have them quickly rise into the stratosphere intact, while they would invariably be wet-oxidized into invisibly-fine hydrated alumina dust during their slow, end-of-life descent through the troposphere, obviating "littering" concerns raised in connection with return-to-Earth of far larger, non-optimized balloons). It's obviously feasible to employ a metallic overcoating of the required thickness applied to an appropriate thickness of a stronger dielectric, e.g., a modern plastic film such as polyaramid or polybenzoxazole, in order to gain durability. (The metallic overcoating would then serve its sunlight-scattering function and would also protect the super-strength plastic film from stratospheric photochemical damage.)

This particular insolation-scattering solution has a much less pronounced dispersion than does the Rayleigh scattering one: it only scatters more strongly with the half-power of the photon frequency (rather than the fourth). Its two distinctive features are that it's an approach which *manifestly* can be implemented without any human machinery leaving the surface of the Earth and it's a scattering system which quickly assumes and thereafter maintains a designed-in altitude in the stratosphere, e.g., so that its meridional transport features will be known *a priori*. Moreover, its effectiveness could be nearly doubled by applying a somewhat heavier coating of LWIR-reflecting material (e.g., a small band-gap semiconductor) to one of the two sheets of film used in balloon manufacture, so that the upper metal-coated hemisphere of each balloon would scatter sunlight back into space, while its lower semiconductor-coated hemisphere would scatter Earth-emitted LWIR radiation back Earth-ward.

Quasi-Resonant Scatterers. A third approach involves the use of resonant – actually quasi-resonant – scatterers, also deployed in the stratosphere.[35] While the potential mass efficiency of this class of scatterers is singularly high, practical considerations centered on photochemical durability in the stratosphere indicate that total masses of 10^6 tons of material may have to be deployed[36] – still modest-scale systems[37] which moreover may have to be replaced only twice per

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[35] Resonant absorption and (quasi-isotropic) fluorescent re-radiation of solar (near-)optical photons is an incompletely-compelling candidate mechanism for *scattering units* primarily because even atoms with full-dipole-transition oscillator strengths in the (near-)visible spectrum absorb with maximum radiative strength only over relatively very small wavelength intervals ($\Delta\omega/\omega \sim 10^{-7}$) and secondarily because such strong absorption is typically seen only in metallic gases (and similarly low-density, effectively-collisionless circumstances, in which the natural width of the transition is a regrettably large fraction of its full width). However, the intrinsic mass efficiency of *scattering units* comprised of a set of resonant absorbers could be expected to be extremely high, and it likely is worth considerable applied photophysics experimental effort to spectrally broaden such resonant transitions to cover ~2% of the solar spectrum. Normal matter never works harder in sustainable electromagnetic terms than when it's scattering radiation on a full electric-dipole-strength transition at the maximum rate given by that transition's Einstein A coefficient ($\sim 10^8$ sec^{-1}, for the full-dipole-strength optical transitions of present interest): i.e., an alkali-metal atom (e.g., Li) will process $\sim 3 \times 10^{-11}$ W of resonant radiation ($\leq 10^8$ photons/sec, each of 1.8 eV or 3×10^{-12} ergs energy) for a mass-cost of 10^{-23} grams (e.g., an Li^6 atom, scattering on its 6708 Å resonant transition) – which corresponds to a specific scattering power of 3×10^{12} W/gm(!). If it were feasible to exercise matter this vigorously in *scattering units*, then the working-mass of an entire *scattering system* would be only ~1 kg. However, the $\leq 10^{18}$ photons/cm^2-sec of (near-)optical solar flux at 1 AU only present $\sim 10^{11}$ photons/cm^2-sec within the ~30 MHz absorption-line of a typical full electric-dipole-strength optical resonant transition, which has a characteristic peak absorption cross-section $\sigma \sim 3 \times 10^{-10}$ cm^2 (i.e., $\sigma \sim \lambda^2/4\pi$, with $\lambda \sim 6 \times 10^{-5}$ cm). Thus, such an atom only processes ~30 photons/sec when hung-in-space in 1 AU sunlight, i.e., it works at only 3×10^{-7} of its maximum feasible scattering-rate. Instead of 1 kg of *scattering unit*-mass, 3×10^9 grams, or 3000 tons, would have to be employed – moreover, as a scattering-disc of free atoms positioned on the Sun-Earth line. Nonetheless, this is a small mass for the "active" component of a full-scale insolation modulation system; it motivates serious consideration of options based on resonant scattering physics.

[36] Intercalation-loading any of the new nanometer-scale poly-carbon structures with fully-enclosed interiors (e.g., C_{60} buckyballs, graphitic nanotubes, etc.) with alkali metal atoms (e.g., as has already been done, using K and Rb, in order to generate moderately high-temperature superconductors) might constitute a useful [packaging+spectral broadening] means which would simultaneously protect the contained species from oxidation and would appropriately broaden its resonant transition. At least some of these structures, e.g., nanotubes, can be sized to "semi-snugly fit" the atom being so caged, so that its outer-electronic-shell-based resonant transition could be broadened to the required extent by either a RMS environmental variation from one caged atom to another of $\sim 4 \times 10^{-3}$ Ry or an equivalent variability-in-time of the caged atom's environment.

If the *scattering system* so constituted were to be made of ~unity optical thickness on these broadened resonant transitions, then this unit-optical-depth system would effectively reflect ~50% of the incident in-band solar radiation back into space; thus, there is a requirement for an effective width of 2% of the solar spectrum near the Planck peak for a full-scale insolation modulation system. These *scattering units* might be positioned in the stratosphere; however, atmospheric positioning imposes a diurnal efficiency penalty, relative to positioning in a scattering-disc on the Earth-Sun line. Also, since a cage for a Li^6 atom may have a mass ~120 times that of the caged atom itself, the 3000 tons of full electric dipole strength optical scatterer-in-a-disc intrinsically required to scatter 2% of the solar spectral radiance at 1 AU might be increased to ~750,000 tons with the concatenated diurnal efficiency penalty and the [packaging+spectral broadening] "mass overhead" of a C_{60}

decade. For near-term, relatively low-risk insolation modulation studies, we propose the use of sub-microscopic particulates composed of frozen perfluorohydrocarbon "nano-droplets" loaded with embedded molecules of selected organic dyes.[38] The total cost-to-own such a full-scale insolation modulation system may be quite competitive – of the order of \$0.3-0.75 billion/year.

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buckyball.

A distinctly different alternative route to realizing such high-strength, broadband quasi-resonant scattering of (near-)optical radiation is based upon organic dye molecules which, in solution, exhibit rather ideally the high oscillator strengths and broadband absorption desired in the present application. While isolated dye molecules exhibit fine structure-rich absorption/fluorescence on their electronic transitions in the (near-)visible spectrum due to concatenated effects of myriad rotational and vibrational splittings, solvent-broadening effects smear the spectrum of dye molecules-in-solution into a featureless continuum – without significantly diminishing the frequency-integrated radiative strengths of the principal interband electronic transitions. Highly concentrated gels of such dyes – e.g., ones derived from low vapor pressure solvents which are "glasses" at stratospheric temperatures, such as the higher molecular weight perfluoroalkanes, may be expected to serve aptly as *scattering units* of still quite high mass-efficiency, ones for which the corresponding *scattering system* mass may be not much greater than that whose *scattering units* are caged alkali/alkaline-earth metal atoms: ~10^6 tons. Materials such as Al or Si, which auto-coat with durable, oxygen-impervious, high-integrity oxide-skins of only a few monolayers thickness, might be aptly employed in lieu of graphitic nanotubes for transparently jacketing such dye-loaded-glasses against stratospheric conditions. Alternatively, use of perfluorohydrocarbons as the dye-bearing material may obviate the need for any protective jacketing, as well as simplify the mass-production of such *scattering units*. The corresponding *scattering systems* may be the ones of choice within this preferred class of quasi-resonant *scattering units*, simply because the dye-bearing fluid could be stratospherically dispersed from an airplane tank as a suitably fine aerosol, the individual nano-particles of which would quick-freeze at stratospheric temperatures and thereupon become photochemically inert over multi-year time-scales. While significantly greater total mass might have to be deployed to constitute such a *scattering system*, the simplicity and relatively low technical risk with which the system could be created and deployed might be an overriding consideration.

How much total mass would be required for each of these alternatives can be reliably estimated from spectroscopic measurements of such metal atom- or dye molecule-loaded nano-containers, i.e., what the absorption spectra and oscillator strengths of the as-packaged materials actually are. After such scoping-level measurements, it will likely be productive to prepare ton-quantities of such quasi-resonant scattering material, disperse it into the stratosphere and then measure the residence time and global distribution of the *scattering units*, e.g., with ground-based range-gated, spectrally-resolved lidar systems. Such modest quantities should be very readily prepared and dispersed, and can be argued from first principles to not have any discernible global effects. Such measurements, in turn, should provide a reliable basis for predicting the effects of 10^3-10^4 greater quantities of such *scattering units*, i.e., their utility as a full-scale insolation modulation system. It's also worth noting-in-passing that the resonant transitions chosen to be intercalation-broadened – or those glassed-in dyes chosen to absorb-&-fluoresce – likely could be selected to lie exclusively in the near-UV or -IR portions of the solar spectral radiance on the Earth's atmosphere, so that the resulting 'spectral notching' of sunlight as seen at or near the Earth's surface would be invisible to people, just as the near-IR solar spectral notchings due to absorption by atmospheric H_2O already are. The as-perceived ‘‘environmental impact’’ of such spectrally-notched insolation subtraction would thereby be essentially zero.

[37] We estimate that an as-deployed caged metal atom-based full-scale scattering system may have a total mass of 7.5×10^5 tons. Due both to higher molecular weight and lower unit radiative strength of dye molecules relative to Li atoms – offset somewhat by proportionately lower "mass overhead" – an organic dye-based system may have a total system mass of ~10^6 tons. (In spite of its greater mass, a dye-based system may be preferred because its spectrally broadened features are readily attained and maintained.) The ≤\$500 million deployment cost of such a dye-based system would likely be considerably less than its materials cost, which we estimate as ~\$1 billion.

Fine-Grained Insolation Modulation. We note technical possibilities of modulating insolation in a latitude-dependent manner. Consistent with the slow latitudinal mixing-time of the stratosphere well above the tropopause, different amounts of scattering material might be deployed (e.g., at middle stratospheric altitudes, ~25 km) at different latitudes, so as to vary the magnitude of insolation modulation for relatively narrow latitudinal bands around the Earth, e.g., to reduce heating of the tropics by preferential loading of the mid-stratospheric tropical reservoir with insolation scatterer.

Indeed, scatterers of sunlight could be deployed at some latitudes to decrement insolation, while scatterers of Earth-emitted long-wavelength infrared radiation (which effectively increment insolation) could be deployed at other latitudes.[39] Differential cooling and heating, respectively, of underlying land-and-ocean latitudinal bands could thereby be accomplished. Furthermore, use of scatterers of varying stratospheric residence times to simultaneously modulate insolation and LWIR radiative losses in a specified latitude band might be employed to fine-tune, e.g., diurnal or seasonal temperature variability.[40]

Conclusions. We have reviewed all the approaches known to us which appear to be of practical significance with respect to addressing the large-scale thermal effects of climate failure – both

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[38] We term this approach "quasi-resonant" because it involves spreading out the exceedingly intense, pure hue arising from resonant absorption and fluorescent emission of light by selected organic molecules into broad bands of still quite intense absorption-fluorescence by these molecules when intimately mixed with other materials. We provisionally choose the perfluorohydrocarbons as the "other materials," because their durability in the even more demanding solar UV/EUV and atomic oxygen environments of low Earth orbit has been demonstrated on the Long-Duration Exposure Facility. We propose to load one or more of these dyes, selected for high radiative strength in either the near-UV or near-IR spectral bands, in a high-boiling fluorocarbon liquid and then to disperse ultra-small droplets of this liquid in the stratosphere, where they will freeze and thereafter provide effective protection against oxidation of the dye molecules which they carry – in addition to not perturbing stratospheric photochemistry.

[39] Such a system might have to be comprised of scatterers designed to have stratospheric residence times significantly less than five years, so that they would e.g., vertically, exit the stratosphere before they had migrated in latitude to unacceptable extents. It appears feasible-in-principle to exploit the stiffly altitude-dependent meridional transport in the lower-to-middle stratosphere to move scattering material poleward from equatorial deployments at most any desired mean rate between $\geq 10\ \mathrm{yr}^{-1}$ and $\leq 0.2\ \mathrm{yr}^{-1}$.

[40] The significance of design optimization to minimize deployed system masses becomes more apparent when considering deployment options featuring post-deployment operational intervals much less than the greatest attainable (~5 years). Deployment mass-rates and costs may become quite burdensome for, e.g., single-month residence times just above the tropopause, unless near-optimally designed scatterers are employed.

global warming and Ice Ages – from the perspective of insolation modulation. In the course of this review, we have applied fundamental physical design principles to mass-optimize several previous proposals in order to enhance their practicality, and we have been able to remove more than an order-of-magnitude of superfluous mass from some earlier conceptual designs. Two insolation modulation systems which we have considered – quasi-resonant scatterers for intra-atmospheric applications and the small-angle-scattering system for deep space use – are apparently novel. These involve total system masses of the order of 10^3-10^6 tons – which is 2-5 orders of magnitude less mass than that of the most interesting previous proposals. We conclude that the insolation modulation approach to prevention of climate failure is certainly technically feasible-in-principle, and that the total costs-to-own its best examples may be *de minimis*.

We believe that research along several lines to study the deployment and operation in sub-scale – perhaps 10^{-3} of a full-scale, 1% insolation-equivalent system – of appropriate scatterers of sunlight is justified immediately by considerations of basic technical feasibility and possible cost-to-benefit. Summary discussions such as those sketched here can only outline the directions to consider. However, even very preliminary estimates of performance and practicality suffice to make us optimistic about ultimate workability and utility.

Success can be expected to be more significant than merely counteracting the global climate modifications arising from large-scale injection of greenhouse gases. Straightforward modifications of what we have discussed including the scattering not of incoming sunlight but of the long-wavelength infrared radiation emitted by the Earth could be effective in preventing onset of both "little" and full-sized Ice Ages.[41] These may occur with little warning, seemingly at any time, and could severely impact human affairs on notably brief time-scales.[42] Indeed, the Earth's

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[41] Both types of space-based scattering systems – high-angle-scattering ones in LEO and small-angle-scattering ones on the Earth-Sun line – may be used to scatter sunlight onto the Earth that otherwise would have passed nearby it. "Self-lofting blue-UV chaff" could be transformed into "self-lofting LWIR chaff" by replacing its metal shell with a semiconductor one chosen to have a direct (for reasons of mass efficiency) band-gap of a few tenths of an eV – energetic enough to reflect LWIR radiation coming up from the Earth's surface and lower atmosphere but of sufficiently low energy to pass virtually all incoming solar photons without significant attenuation (e.g., InSb). The very low mass small-angle-scattering system in deep space can be readily converted to direct additional sunlight onto the Earth from a position slightly offset from the Earth-Sun axis, rather than scatter it away from an on-axis location.

[42] See, e.g., Greenland Ice Core Project (GRIP) Members, Climate instability during the last interglacial period recorded in the GRIP ice core, *Nature* **364**, 203-7 (1993) for a discussion of observed "few decade to centuries" large-amplitude temperature variability of the Northern Hemisphere during the interglacial period immediately preceding the present one. A repetition of the 7-decade "cold snap"

climate system may manifest finite-amplitude instability along several axes, with small perturbations occasionally resulting in large shifts, some swiftly executed.[43]

Greenhouse warming of the Earth due to human activities is a *possibility*,[44] moreover one for which mitigative/remedial actions of the types proposed here can be at once *deliberate* and *effective*.[45] In contrast, Ice Age-severity cooling, another in the series of events that have occurred quasi-periodically many times during the last 1.2 million years,[46] is a practical *certainty*. Moreover, a several-decade duration "cold snap" of Ice Age Maximum temperature-drop is known to have occurred in the Northern Hemisphere with essentially no warning during the last interglacial period, under precursor climatic conditions only slightly warmer than the present-day one.[47]

Today, our scientific knowledge and our technological capability already are likely sufficient to provide solutions to these problems; both knowledge and capability in time-to-come will certainly be greater. Whether exercising of present capability can be done in an internationally acceptable way is an undeniably difficult issue, but one seemingly far simpler than securing international consensus on near-term, large-scale reductions in fossil fuel-based energy production[48] –

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of the ~14° C peak magnitude inferred from examination of the Greenland cores might reduce arable land world-wide by – at the very least – 1% per year following its abrupt onset, a rate which would result in large-scale famine on single-decade time-frames, as planetary food reserves become exhausted. (The inferred time-scale of the associated shifts in atmospheric circulation occurring during these "fast" events is 1-3 decades, which is comparable with that inferred to have occurred during termination of the most recent Ice Age.)

[43] E.g., Broecker WS, Cooling the tropics, *Nature* **376**, 213-4 (1995) concludes "The palaeoclimate record shouts out to us that, far from being self-stabilizing, the Earth's climate system is an ornery beast which overreacts even to small nudges."

[44] Hasselmann K, Are We Seeing Greenhouse Warming? *Science* **276**, 914 (1997).

[45] See, e.g., Wigley TML, Richels R and Edmonds J, Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations, *Nature* **379**, 240-3 (1996), where it is demonstrated that "business as usual" in fossil fuel-based energy production for the next three decades does <u>not</u> doom the Earth to global warming in excess of 2°C, if reasonable measures are taken thereafter. We note that insolation modulation systems can be studied-in-subscale and then deployed on single-decade time-scales, short compared to the onset of any global warming (or cooling) currently considered.

[46] Imbrie J et al., On the Structure and Origin of Major Glaciation Cycles 2. The 100,000-Year Cycle, *Paleoceanography* **8**, 699-735 (1993).

[47] Greenland Ice Core Project (GRIP) Members, Climate instability during the last interglacial period recorded in the GRIP ice core, *Nature* **364**, 203-7 (1993)

especially in a world exhibiting very large geographical and cultural differences in *per capita* energy use, past, present and future.

We believe that, prior to any actual deployment of any scattering system aimed at full-scale 1% insolation modulation, completely transparent and fully international research in sub-scale could result in public opinion conducive to a reasonable technology-based approach to prevention of large-scale climatic failures of all types. International cooperation in the research phase, based on complete openness, is necessary and may be sufficient to secure the understanding and support without which any of these approaches will fail.

The purpose of this paper is not to advocate definite solutions. It is only to augment the scientific effort to find solutions of general acceptability and benefit.

The blame for "bad weather" may be too heavy for any human to bear. But, we hope, thinking before acting might be acceptable.

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[48] While we claim no particular expertise in policy matters, we note expert opinion to the effect that ". . .stabilization [of atmospheric CO_2 levels] requires an eventual and sustained reduction of emissions to substantially below current levels" [Wigley TML, Richels R and Edmonds J, Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations, *Nature* **379**, 240-3 (1996)] and we estimate that "substantial" worldwide reduction in fossil fuel usage over the next several decades will not occur without substantial likelihood of inducing major conflict.

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