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

---

[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"