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ACTIVE CLIMATE STABILIZATION:

Presently-Feasible Albedo-Control Approaches to Prevention of *Both* Types of Climate Change

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Opinions expressed herein are those of the authors only.

WHERE WE ARE

- The Earth's *remarkably* cold, these days
  - Lowest mean temperature percentile since the Cambrian Explosion, at start-Paleozoic, ~545 Mya
- But we believe we don't want it to warm up *at all*
  - Indeed, since even a ~1% warming (~3± K) may be so bad, wouldn't a ~1% cooling be quite good?
    - Or are we 'magically' at precisely the "Goldilocks optimum?"
- And we're currently thinking of spending a lot of money-&-effort to turn a 'weak handle' on climate – atmospheric [CO_2] – to keep it from warming significantly, (most of) a century hence
  - When humanity's technological posture surely will be far different from today's (cf. 1929-54 postures)
- So what about (present-time) alternatives?
  - Why not consider changing the radiative properties of the Earth('s atmosphere), which directly control the temperature profiles of the Earth's fluid envelopes?
  - *Technical management* of radiative forcing – vs. *bureaucratic management* of atmospheric inputs

RADIATIVE FORCING MANAGEMENT I.

- How to do it? What's the cost? What are the uncertainties? the 'externalities'?
  - See, e.g., http://www.llnl.gov/global-warm/
  - *Not* a new subject; many ideas are non-novel
    - E.g., see Web page papers for references
  - This work: albedo engineering-*extension/-optimization*
    - Minimization of masses, costs, uncertainties, side-effects, …
    - …with a few new schemes added, e.g., prevention of Ice Ages
    - Basic implementation considerations
- Respect for the pertinent mandate of the *UN Framework Convention on Climate Change*
  - ***"...policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."***
  - What's the least expensive way to stabilize the climate at whatever the desired value(s) may be?
- Prevention of abrupt-onset 'climate catastrophes'
  - E.g., 5-15 K 'cold snaps' GRIP-seen during Eemian

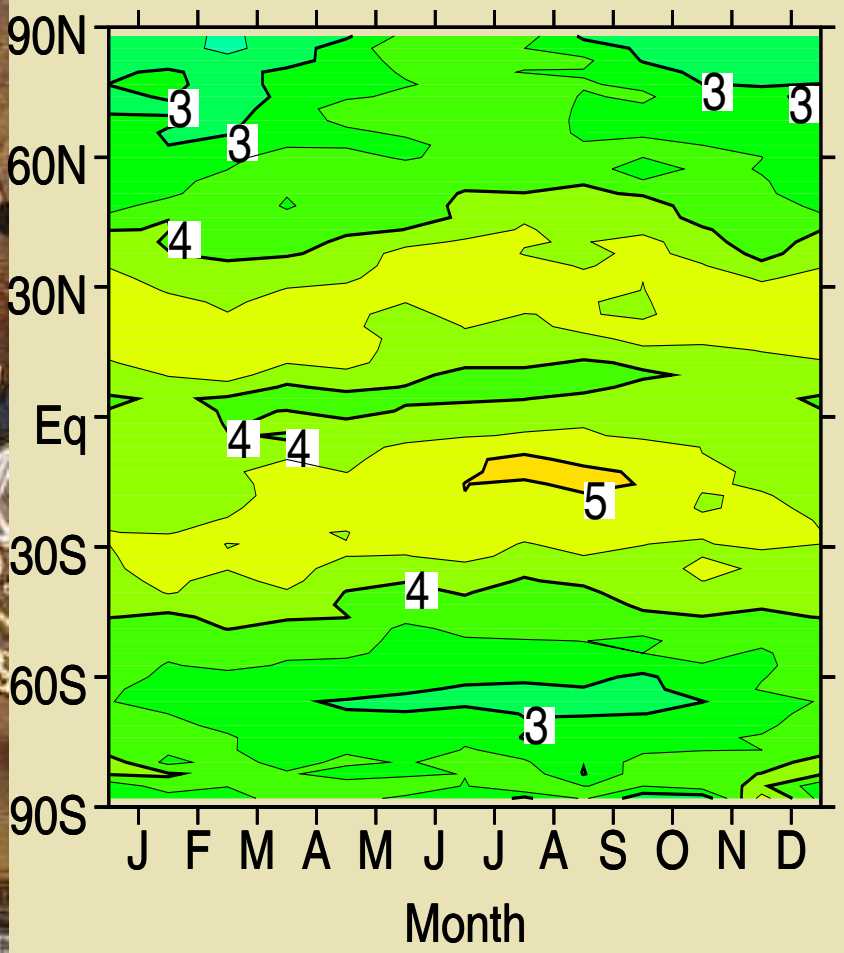
RADIATIVE FORCING MANAGEMENT II.

- (Projected-to-2100±) **warming** problem scale
  - Want to reject ~2% of sunlight-equivalent
    - I.e., ~4 Watts/m^2, space- & time-averaged
    - Atmospheric [CO_2] of 560 ppm (2X 1890 level)
  - Equivalent to blocking ~10^6 km^2 of Earth's disc
  - Desire Earth's thermal radiation to pass *out*, and/or while Sun's light doesn't come *in*
- (Projected-to-3000±) **cooling** problem scale
  - 2150± [CO_2] pulse then sunk into ocean
  - Want to gain extra ~4% of sunlight-equivalent
  - Desire Earth's thermal radiation to stay *in*, and/or while extra sunlight also comes *in*
- Require all 'standard features' of techno-fixes
  - Automatic, certain, reasonably-fast reversibility
  - Min. unpleasant/max. pleasant side-effects
  - Low costs, some collateral benefits(?), ….
  - ~20X wavelength factor available to exploit

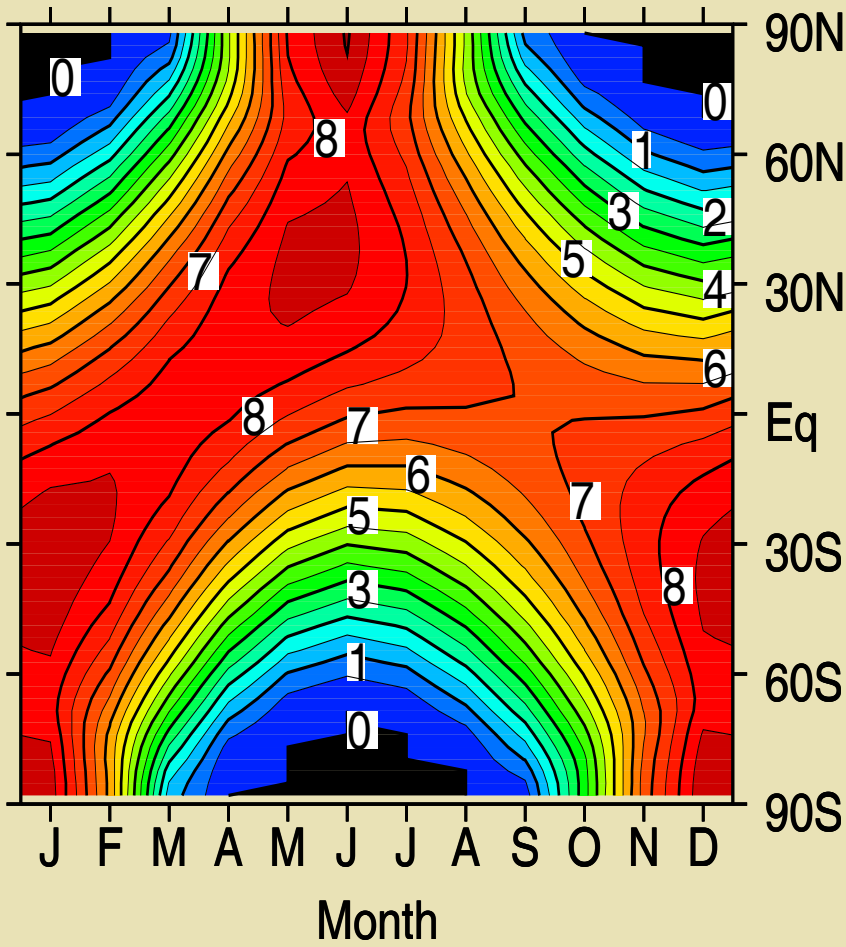
RADIATIVE FORCING MANAGEMENT III.

- So we scatter away some fraction – ~2% – of the 2100± insolation. What then?
  - Earth's space- and time-**averaged** temperature *must* drop to the desired 'previous value,' but…
  - …everybody's climate *surely* gets messed up! [Schneider, 1996]
    - And 'mere' preservation of averages doesn't "do the job" – all of the meso-climates (politically) must be left unchanged
- ***Surprise! "You can have it all!"***
  - Govindasamy & Caldeira [2%, 2000; 4%, 2002]:
  - Present climatic system has 'deep fundamental modes'
  - Mesoscale climatic features are invariant under the geoengineering-of-interest everywhere, *all the time!*
    - Even through spatially-uniform insolation-decrement forcing has very different space- and time-dependences, relative to CO_2 atmospheric forcing: ***"Marine 'geography'+sea-ice are destiny"***
- Ditto re +4% insolation in ~3000 to stop the Ice Age
  - This degree of climate linearity on the 'warming side' has been model-demonstrated by Caldeira, et al. [2002]

CO_2 radiative forcing from a CO_2 doubling (W / m^2)

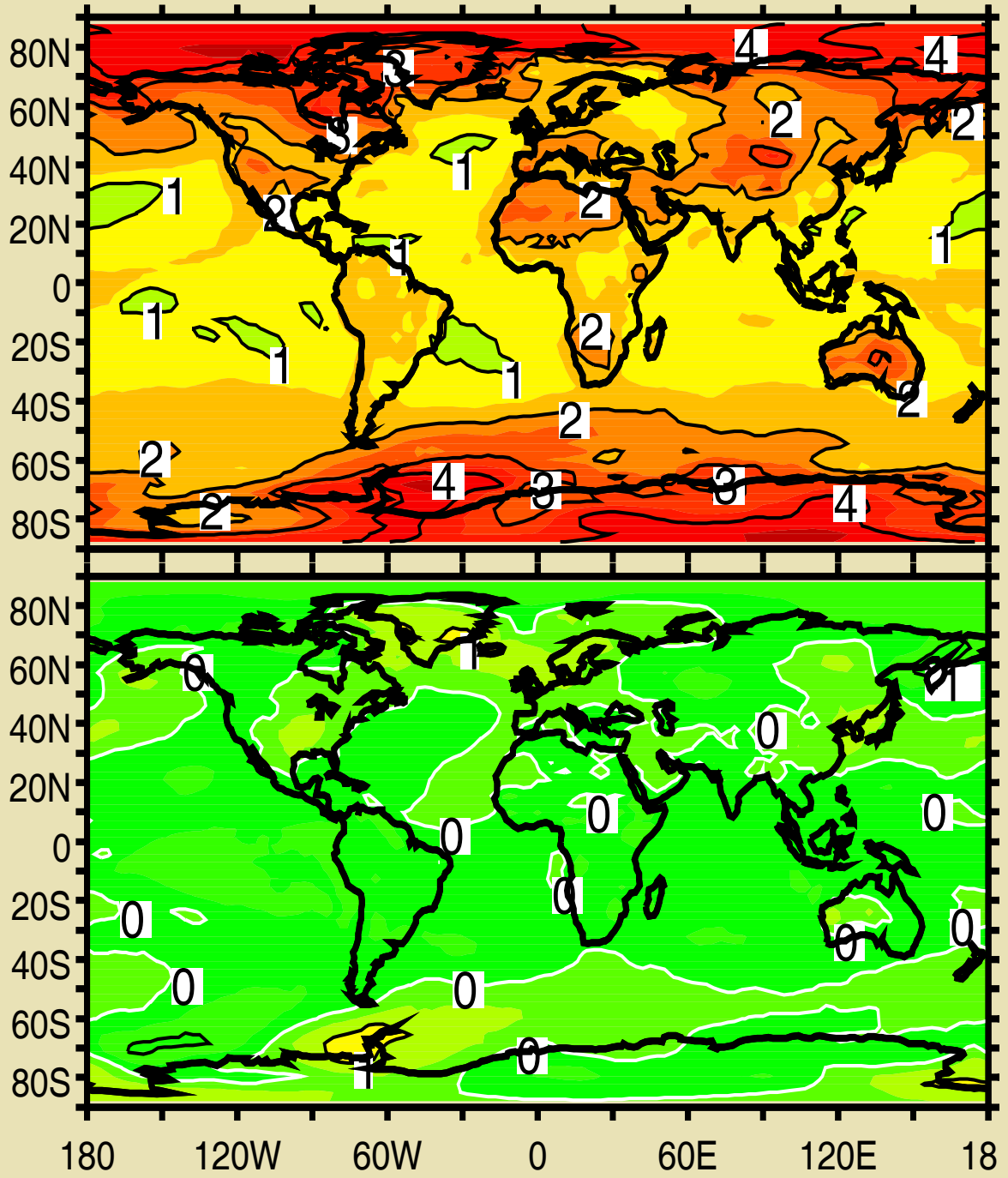


Radiative forcing from 1.8% reduction in solar intensity (W / m^2)



Can these two forcings *possibly* be equivalent???

Ref: Govindasamy and Caldeira (2000)



$2 \times CO_2$

YES, they can!!

$2 \times CO_2$ with 1.7% insolation reduction

Ref: Govindasamy and Caldeira (2000)

RADIATIVE FORCING MANAGEMENT: WAYS-&-MEANS I.

- How best to decrement insolation by ~2%?
- Controlled scattering of incoming sunlight back into space, by *sub-microscopic* minimum-feature-size
  - ***Dielectrics*** – e.g., ~100 nm sulfate aerosol-spherules
  - ***Metals*** – e.g., "UV chaff," super-P metal balloon-ettes
  - ***Resonant scatterers*** – e.g., coated dye molecules
  - ~10^6:10^2:1 'raw' mass-ratios; ~1:20:2 'dressed'
- 'Engineered scatterers' put into the stratosphere
  - Low-rent, unused 'territory' – infinite momentum-sink
  - Variety of positioning technologies are readily available
    - E.g., stay below ozone layer and *actively* altitude-seek
  - Mid-term (~5 yr.) *passive* positional stability (aerosols)
    - Mid-Tropical Stratospheric Reservoir – ~20-25 km altitude
  - ***'Known to work'*** scheme – so noted by '92 NAS Study
    - Dyson & Marland ('79) proposed for [CO_2] warming mitigation
    - Explosive volcanic ejecta "exp'ts." – El Chichon; Mt. Pinatubo
    - 10-30% of desired-in-2100 cooling effects have been observed
      - Albeit 'dirty,' grossly-oversized aerosol lofted to too-low altitudes

RADIATIVE FORCING MANAGEMENT: WAYS-&-MEANS II.

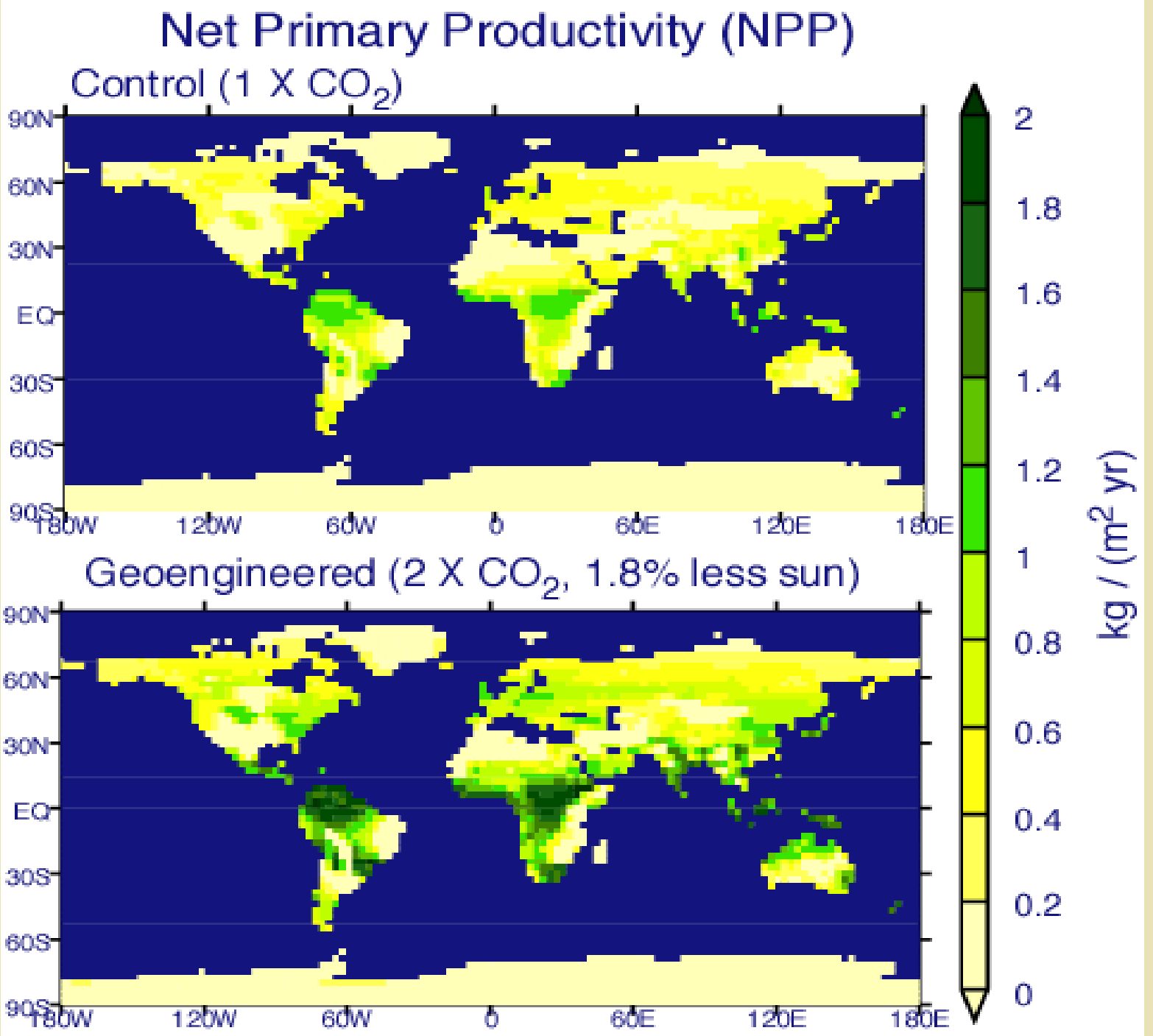
- Issues of blue-violet (e.g., Rayleigh, "optical chaff") scattering of insolation
  - Less solar UV – λ^{-4} dependence (Rayleigh)
    - Deep UV ($\lambda \leq 320$ nm) is severely attenuated
      - Below the ozone layer – layer's photophysics isn't perturbed
      - Lower-air radiative heating decreases with spectral red'n.
    - Less sunburn, skin dysplasia, dermal cancers
      - Lower medical bills, pain-&-suffering, fear,…
    - Less photodamage to plants, e.g., food-crops
      - (Substantially) higher agricultural productivity
    - Bluer mid-day skies
    - More spectacular (redder) twilights
  - No perceptible loss of visible/photosynthetic light
    - "Just as (optically) bright, but slightly cooler"
- Common features of all warming-prevention proposed stratospheric scattering systems
  - Variability in λ-dependence, mass-efficiency, cost,..

RADIATIVE FORCING MANAGEMENT: WAYS-&-MEANS III.

- Operational mass and cost scales
  - For 2% insolation reduction
    - Replacement of steady-state 'natural' attenuation
  - ***Dielectrics:*** largest annual mass (~1 MT – 10^{12} gm) & cost (~$1 B)
    - E.g., lofted by a 'wing' of ~6 high-altitude cargo aircraft
  - ***Metals:*** lowest annual mass (~0.05 MT) & cost (~$0.2 B)
  - ***Resonant scatterers***: intermediate annual mass (~0.5 MT) and upper-end cost (~$1 B)
  - ***Earth-Sol 'L-1' Deflector System***: 0.00003 MT (!)
    - Total mass of 3,000 T emplaced over 100 yrs. – zero maintenance
      - 1 Shuttle-launch per year of construction mass (10^4 km^2 area)
    - 'Raw' – cf. 10 MT previous design; ~0.01 MT 'dressed'
    - ~30 μm-pitch (e.g., Al) metal screen – with ~25 nm 'ribs'
    - Presently indeterminate cost – clearly the long-term winner
    - Enduring defense against Ice Ages and warming episodes
      - Positioned *slightly-off* or *on* the Earth-Sun line, respectively, as needed
- Side effects issues
  - Possible stratospheric (photo)chemistry impacts
    - Particulates can be engineered to be low-reactivity & -'hanging'
    - Likewise for optical chaff & super-pressure balloon-ettes
  - Scatterers 'wash out' in polar vortex precipitation
    - Aerosols: small fraction of existing air-borne particulate – and chemically similar/identical (e.g., SO_2, Al_2O_3,..)
    - Al UV chaff and metallic super-pressure balloon-ettes: wet oxidation in troposphere during descent converts into Al_2O_3 dust

RADIATIVE FORCING MANAGEMENT: WAYS-&-MEANS IV.

- Side effects issues, cont'd.
  - Plants and animals both do better with less solar UV and the same visible insolation – and, *crucially*, additional CO_2 'aero-fertilization'
    - Land-plant 'primary productivity' nearly doubles (2X)
      - {IBIS+CCM3} model-estimates; 4X much better than 2X
        - Govindasamy, Caldeira & Duffy [2002]
      - More CO_2 'food' – assisted by less thermal-transpiration stress
      - Imputed agricultural economic gains not much less than ***$1 T/yr.***
      - **Feeding the 3-4 B additional people in 2100 now looks do-able without requiring more major food-production 'miracles'**
      - **Moreover, regions of 'primary productivity' gains map well onto areas of greatest estimated human population growth**
    - All near-surface animals and all plants thrive with lessened photodamage (i.e., due to drastically reduced UV-B)
      - Energy spent repairing photodamage now goes to growth
    - People are less threatened by sunburn, skin cancer
      - Estimated economic savings of ~$20 B/yr. – and ~$10^5$ lives



Ref: Govindasamy, Caldeira & Duffy (2002)

RADIATIVE FORCING MANAGEMENT: WAYS-&-MEANS V.

- Ice Age prevention
  - May now be ~5 millennia overdue [Ruddiman, 2003]
    - Mid-Holocene forest-clearing, agricultural onset "near miss"?
  - After most of early 3rd Millennium CO_2 pulse is ocean-sunk, what halts re-glaciation in Canada's north?
- Three approaches to "inexhaustible" greenhouse
  - "LWIR chaff": 10 μm mesh Al screen & 0.1 μm 'ribs'
    - Comparable areal mass-density as "UV chaff"
    - Annual stratospheric lofting requirements of ~0.1 MT/year for +4 K mean global temperature-increase: ~$0.4 B annual cost
  - Semiconductor (e.g., Si)-walled super-P balloon-ettes
    - Again, pass optical insolation; reflect Earth-sourced LWIR
  - Near-L-1 diffractive screen moves aside from Earth-Sun axis, scatters 'missed' insolation onto the Earth
    - Same screen as precluded 'excessive' warming earlier
      - "Tacks" a bit differently into Sun's radiation+gravitational pressure
    - Agricultural benefit retained – photosynthetic light enhanced

CONCLUSIONS I.

- *Active technical management* of radiative forcing (albedo engineering) has an all-planet estimated cost of $0.2-1 B/year – for a 2% insolation reduction
  - Depending on particular technology chosen
    - 4 independent ones to choose from
      - Aerosols, "UV chaff," super-P metallic balloon-ettes, L-1 shade
    - 3 practical immediately – and 1 is performance-proven
    - Quickly, cheaply, reversibly testable in sub-scale
- Tiny cost, compared to $N *hundred* B/year for *bureaucratic management* of gas inputs
  - 1<N<4, for U.S. alone (variously estimated)
- *UN Framework Convention on Climate Change's* Article III clearly mandates technical (vs. bureaucratic) management
  - ***"…ensure global benefits at the lowest possible cost."***
    – Art. III, Sect. 3

CONCLUSIONS II.

- Human interests clearly demand active technical (vs. bureaucratic) management of 'global warming'
  - ***Twice as great land-plant 'primary productivity' is on-offer***
    - The 'green side' of 2X increased atmospheric [CO_2]
    - Better nutrition for the 21st century's greatly increased population – without more food-production miracles being required
      - More-&-better food gained for the same effort, cost, land-use, water, …
  - ***Greatly reduced "sun damage" to humans-&-property, plants,…***
  - Enhanced atmospheric aesthetics: sunrises/sunsets, sky-blueness,…
- An experimental program to explore stratospheric scatterers *in sub-scale* should commence forthwith
  - 'Standard' theoretical/modeling/experimental program
    - Scoped at ~$1 B for first third-decade's effort
      - With all plausibly-significant side-effects examined concurrently
    - Tenth of the $3+ B/year currently spent on 'global change' studies
    - Amply justified purely as insurance re rapid-onset climate change
  - Experimental effects auto-liquidate in half-decade time-frames
    - No *rational* concerns re lasting or large-scale implications
  - Instruments very readily detect 10^{-4} $\Delta I/I$ insolation scattering
    - E.g., ~10^{-2} of sub-scale, relative to Mt. Pinatubo's stratospheric loading
  - ***All nations' scientists-&-engineers should participate***
    - A commonly-owned problem calls for a jointly-developed solution
    - Every person's right to a decent 'energy standard-of-living' respected
      - Severe energy rationing not "crammed down the throat" of the Third World
      - Already a widely *rejected* gambit – self-evidently an unethical one