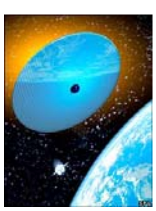
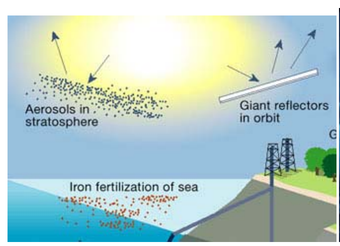
Geoengineering?

- Definition = “intentional large scale manipulation of the environment”
- Can we buy time by cooling the planet artificially?
- Initially ‘taboo’ idea for scientists… but is getting more attention…
  - Slow progress of mitigation effort to reduce CO_2 emissions
  - Evidence for increasing climate impacts (sea-ice, Greenland ice sheet)
  - Maybe we should think about an ‘emergency brake’
  - In 2006: Notorious scientists (Paul Crutzen, Ralph Cicerone) reignited the idea of examining geoengineering feasibility and impacts from a scientific point of view
  - Irreversibility of CO_2-induced climate change (Solomon et al. paper)

Two main solutions

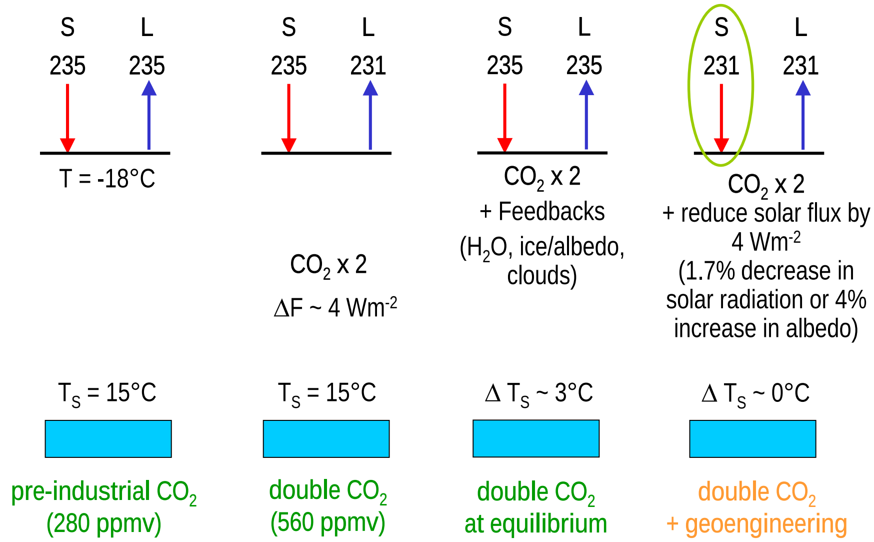
- Remove CO_2 from the atmosphere (sequestration in ocean and/or land) → *Julian Th. March 5*
- Reduce solar radiation (increase Earth’s albedo or reduce incoming solar radiation)





Offsetting climate effects of a CO_2 doubling

Solar (S) and longwave (L) radiation in Wm^{-2} at the top of the atmosphere

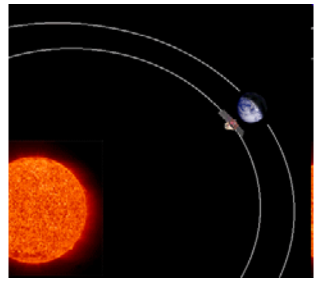


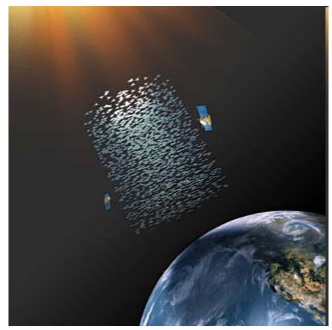
Some proposed ideas for solar radiation management

- Reduce solar constant:
  - "Sunshade" world: screens at the Lagrange point (L1) between Earth and Sun
  - Sunshades in Earth's orbit
- Albedo modification schemes:
  - Albedo enhancement of marine stratocumulus clouds
  - Stratospheric aerosol injections
  - Increasing albedo of land surfaces (white plastic coverings over deserts, bioengineered plants, highly reflective roofs+roads in urban areas)

"Sunshade" world

- Space-based sunshade scattering sunlight away from Earth
- Near inner Lagrange point (P1): 1.5 million km from Earth. Same 1-year orbit as Earth
- Many small autonomous spacecraft: very thin refractive screen. 100,000s meter sized flyers forming a 100,000 km long cloud
- ~ a few trillion $$





Scientific American, Oct. 2008

Early (1989) *J. Br. Interplanet. Soc.*, 42, 567-569
Angel (2006) *PNAS*, 103, 17184-17189

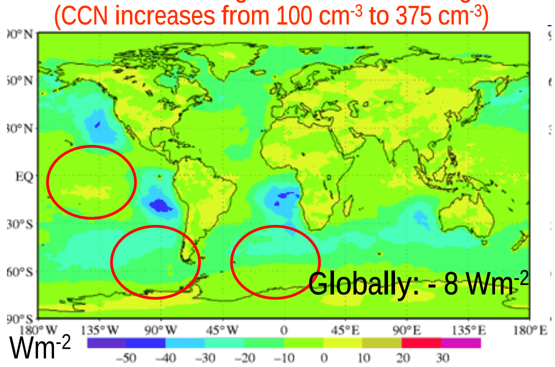
Albedo enhancement of low-level maritime clouds

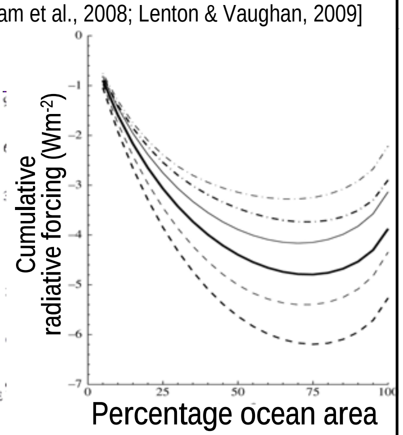
Ship tracks off Western US
NASA/MODIS June 28 2003

Albedo enhancement of low-level maritime clouds

- Seed low-level clouds with sea-salt particles
- Increased cloud condensation nuclei (CCN) → ↓ droplets radius → ↑ albedo (first indirect effect) + ↓ precipitation (longer cloud lifetimes)
- Doubling of CCN in all marine stratiform clouds → albedo increase of ~0.06-0.09, compensates for a 2xCO_2 [Lantham et al., 2008; Lenton & Vaughan, 2009]

Radiative forcing due to cloud seeding
(CCN increases from 100 cm^{-3} to 375 cm^{-3})





Lantham et al. (2008) Phil. Trans. R. Soc. 366, 3969-3987

How could it be done?

- Fleet of 1,500 unmanned spray vessels would be required to produce –3.7 Wm^{-2} cooling.
- Underwater propellers could generate electrical energy. Flettner rotor systems used as 'sails'. Need 2.3 10^8 Watts.
- Cost estimate: $1.5-3 million/spray vessel = $2-4.5 billions

Anton Flettner's first rotor ship, crossing the Atlantic in 1926

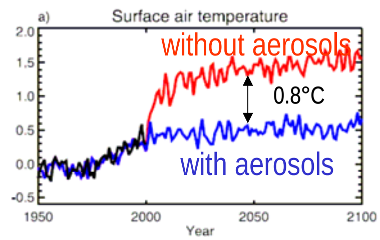
'Cloudia' prototype

Artist's rendition of Flettner spray vessel

Salter et al. (2008) Phil. Trans. R. Soc. 366, 3989-4006

Injection of sulphate aerosols

- Sulphate aerosol scatter solar radiation and affect cloud properties (indirect effect)
- Radiative forcing due to sulphate aerosols: -0.8 Wm^{-2} (direct) and -1 Wm^{-2} (indirect)
- Cooling of ~0.8°C (today, masking GHG forcing)



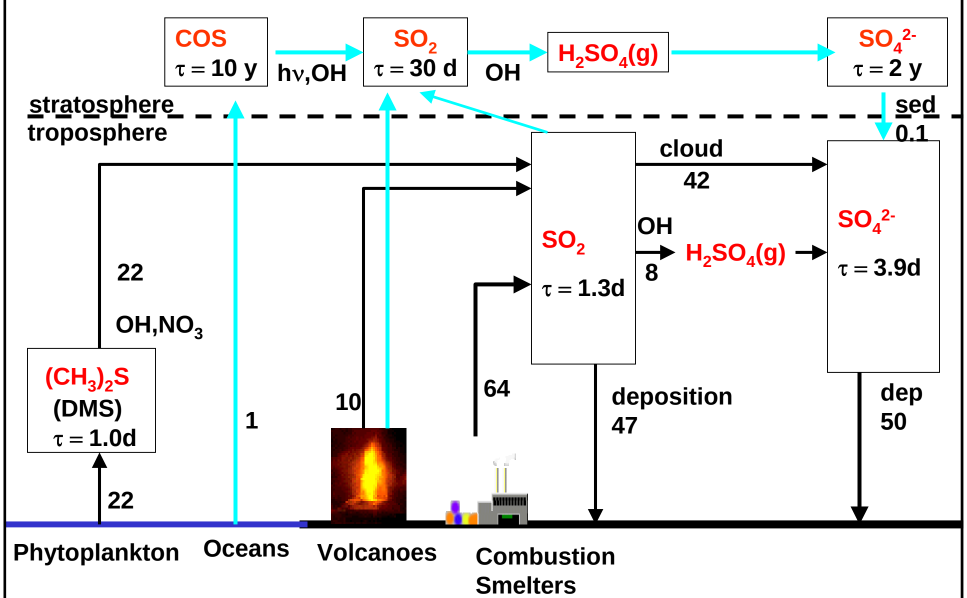
Brasseur & Roeckner (2005) GRL

→ ~~increasing SO_2 emissions by a factor of 3 would offset the effects of CO_2x2 (200 TgS/year)~~

… but severe human health effects + damage to ecosystems (acid rain)

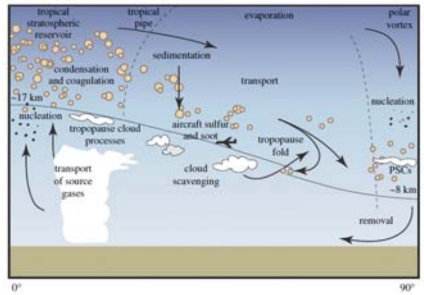
→ *not a viable solution*

GLOBAL SULFUR BUDGET (flux terms in Tg S yr^{-1})



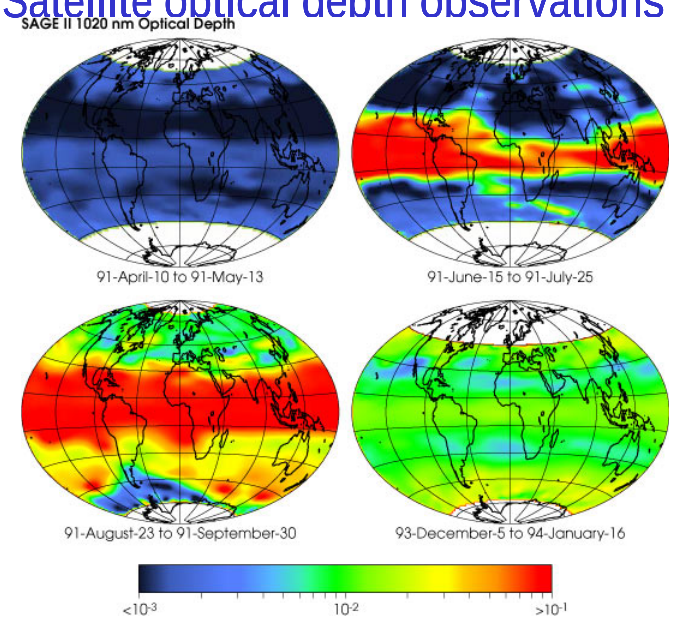
Injection of sulfur in the stratosphere

- Long lifetime in the stratosphere ~1 year (compared to a few days in troposphere) → would need 100 times less sulfur
- Volcanic eruption analog: Mt Pinatubo (1991). For a 10 TgS injection of SO_2 in tropical stratosphere → global mean cooling of 0.5°C (4.5 Wm^{-2} cooling)



Rasch et al. (2008)

Global effects of Mt. Pinatubo: Satellite optical depth observations



http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=4952

Injection of sulfur in the stratosphere

- How much sulfur would be needed to compensate for a doubling of CO_2?
  - 5 TgS/year [Crutzen (2006), Climatic Change 77, 211-219: linear downscaling of Mt. Pinatubo effects]
  - 1.5TgS/yr if small aerosols [Rasch et al. (2008) GRL, 38: coupled climate system model]
  - 1.5-5 TgS/yr [Robock et al. (2008) JGR, 113: OAGCM]
- Aerosol injection scenarios:
  - naval rifles: inject 1 Tg S for $25 billion (NAS 1992)
  - To get 1.5-5 TgS/year it would cost 40-125 billion $/year
  - Equal to 0.1-0.5% of today's Gross Domestic Product or 4-12% of annual global military spending
  - Alternative injections: F15 Eagle fighter jet (500 flights/year → 4 billion $/year) Robock et al. (2009, GRL).

Rasch et al. (2008) Phil. Trans. R. Soc. A, 366, 4007-4037

Impact on stratospheric ozone

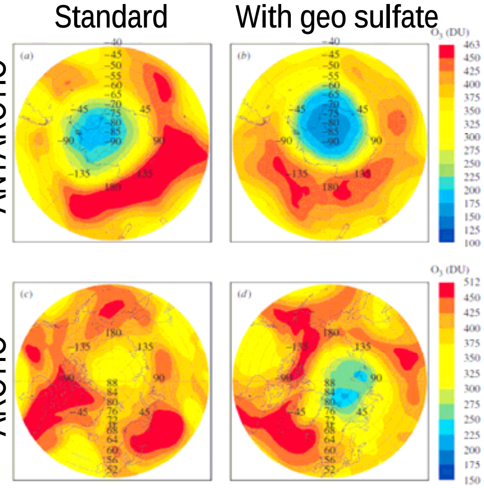
Sulphate aerosols provide surfaces on which chemical reactions leading to ozone loss take place. They also lead to the increased formation of PSCs.

Worsening of stratospheric ozone depletion:
• substantial increase in Arctic ozone depletion especially during cold winters
• delay of 30-70 years in recovery of Antactic ozone layer

Standard | With geo sulfate

ANTARCTIC

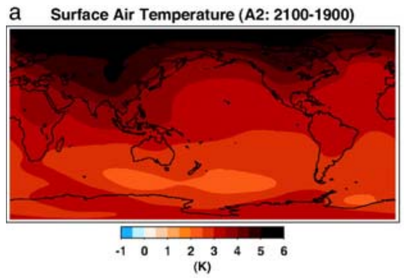
ARCTIC



2025 ozone simulations

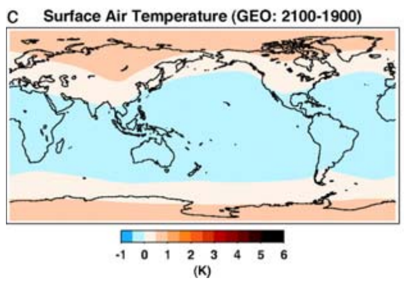
Tilmes et al (2008) *Science*, 320, 1201-1204
Rasch et al. (2008) Phil. Trans. R. Soc. A, 366, 4007-4037

Good news… it seems to work for surface temperature!



2100: A2 scenario

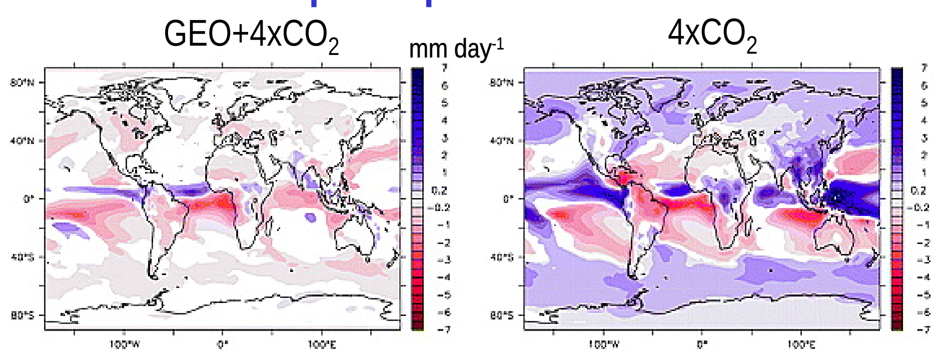
Global mean surface temperature back to pre-industrial levels with slightly colder Tropical temps and warmer high latitudes.



2100:
A2 scenario + sunshade world
(3.7 Wm^{-2} reduction in solar radiation)

Matthews and Caldeira (2007) PNAS, 104, 9949-9954

But… not for precipitation



5% decrease in global precipitation

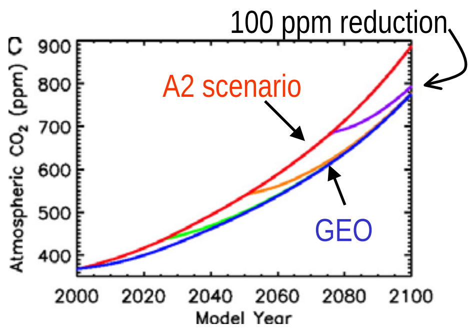
Geoengineered worlds generally drier than pre-industrial climate:
reduced temperatures over tropical oceans → decrease in evaporation → decrease in precipitation

Lunt et al. (2008), GRL, 35.

Impacts on carbon cycle

- Potential increase in the terrestrial carbon sink: increased CO_2 fertilization + lack of temperature change

  Matthews and Caldeira (2007) PNAS, 104, 9949-9954

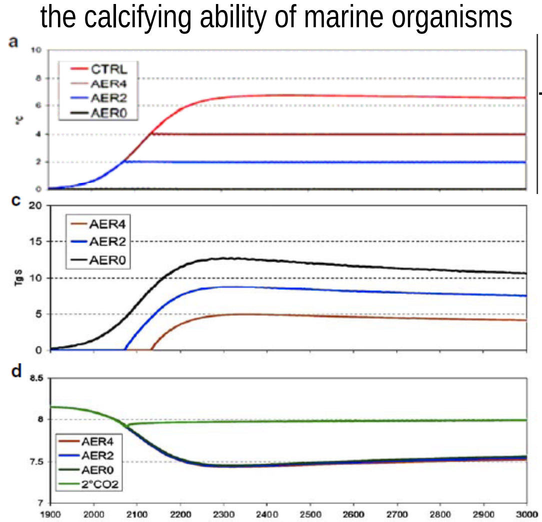


- Potential increase in the oceanic carbon sink: increased CO_2 solubility due to lack of temperature change

  Brovkin et al. (2009) Climatic Change, 92, 2430259

Impacts on carbon cycle (cont.)

- Geoengineering by sulphate aerosol injection (and sunshade) still leads to ocean acidification: average surface ocean pH decreases by 0.7, reducing the calcifying ability of marine organisms



Temperature change

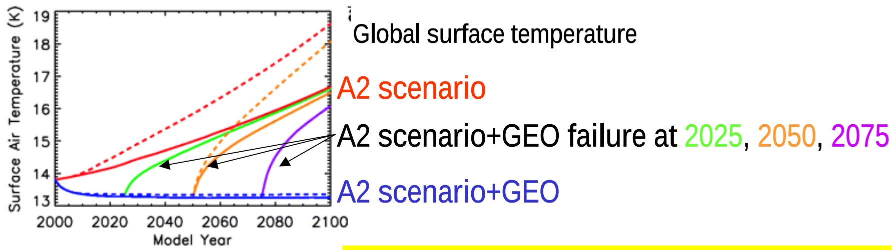
Sulfur injections

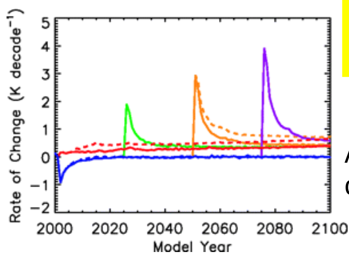
Ocean pH

Brovkin et al. (2009) Climatic Change, 92, 2430259

What would happen if we stopped geoengineering?

- Abrupt technological failure and/or deliberate termination of geoengineering at some point in the future





→*Very large rates of warming: 1-4°C/decade for 10-20 years! (today 0.2 °C/decade)*

Annual rate of temperature change

Matthews and Caldeira (2007) PNAS, 104, 9949-9954

Geoengineering – the good and the bad

- Arguments for…
  - Quick fix to rapid warming (melting ice caps, rising sea levels…) effectively reversing CO_2 warming.
  - Some ideas not that expensive.
- Against…
  - Negative impacts on hydrological cycle, ozone layer…
  - Once started we need to maintain it for centuries
  - Failure of implemented GEO would be catastrophic
  - No cure for ocean acidification
  - Treat symptoms not cause. Excuse not to reduce GHG?
  - Too cheap… country or rich individual could do it unilaterally
  - Uncertainties in science…are models good enough ?
  - Ethical/political questions: how would it be implemented? How do we decide what the temperature should be? Who would decide?…

More in: Robock (2008) 20 reasons why geoengineering may be a bad idea. *Bull. Atomic Scientists*, 64, No. 2, 14-18, 59