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Climate Engineering through Stratospheric Particle Injection

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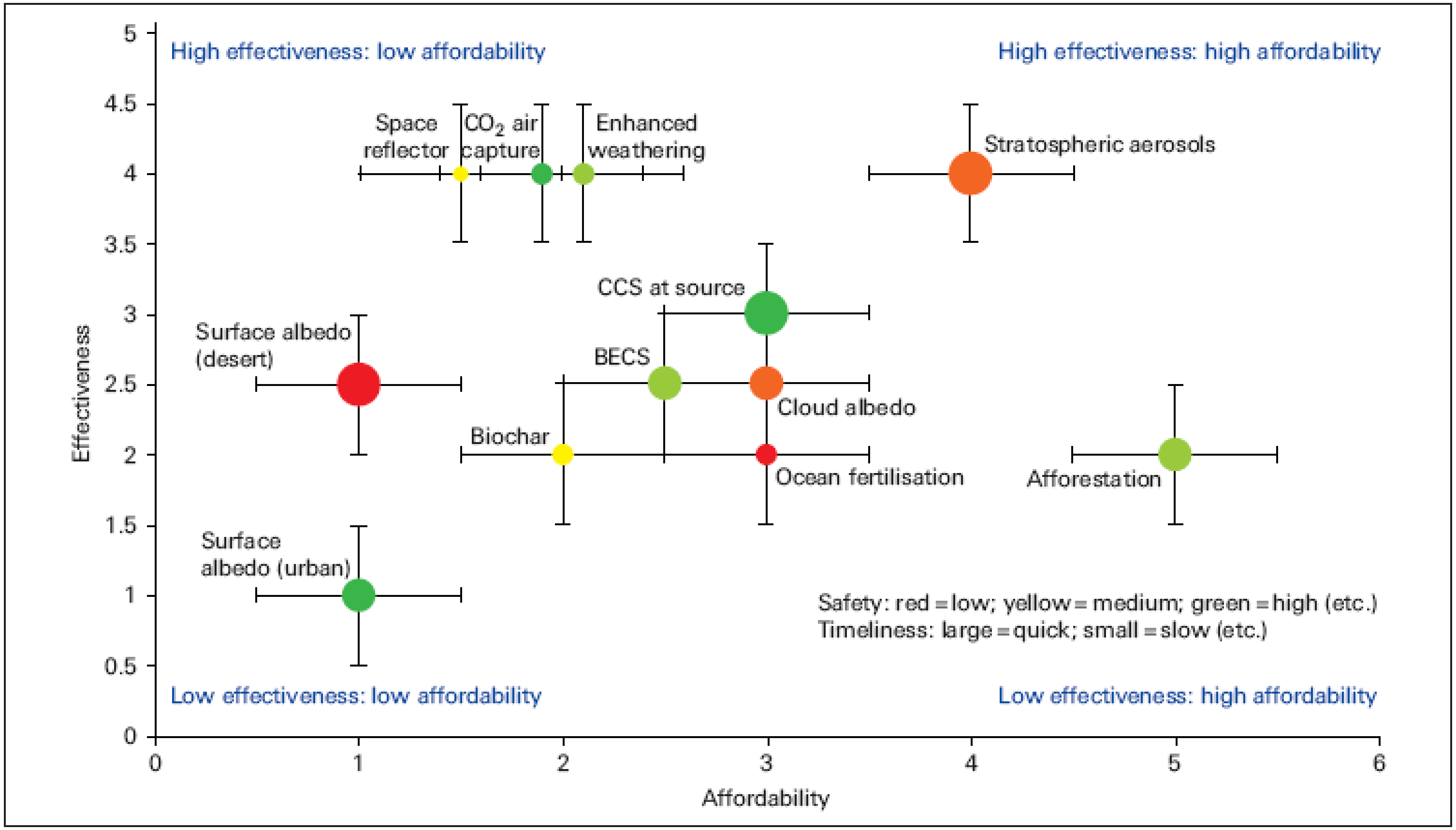
LWEC meeting, BIS, 20th May, 2011

Royal Society Report (2009)



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Outline

- Natural analogues to stratospheric SRM
  - Mt. Pinatubo
    - Quantifying emissions
    - Observing effects
- The SPICE project : Stratospheric Particle Injection for Climate Engineering
  - Breakdown of research effort
  - Feasibility study

Natural Experiments - Mt. Pinatubo, 15 June 1991

August 30, 1984

August 8, 1991

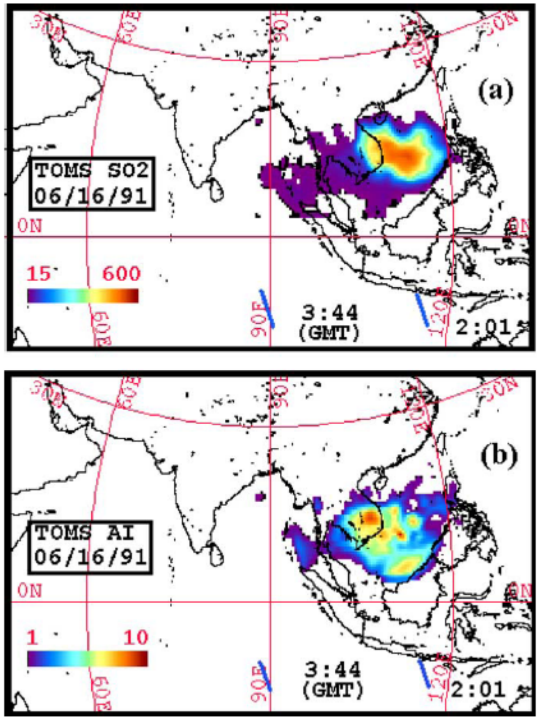


Figure 9. NASA TOMS maps: (a) SO_2 cloud map and (b) AI map. Latitude and longitude grid spacing is 30°. The SO_2 values are represented in Dobson Units (DU), and AI is unitless. The image sensing times are approximately the central pixel sensing time of the starting and ending orbits in GMT as indicated in the figures.

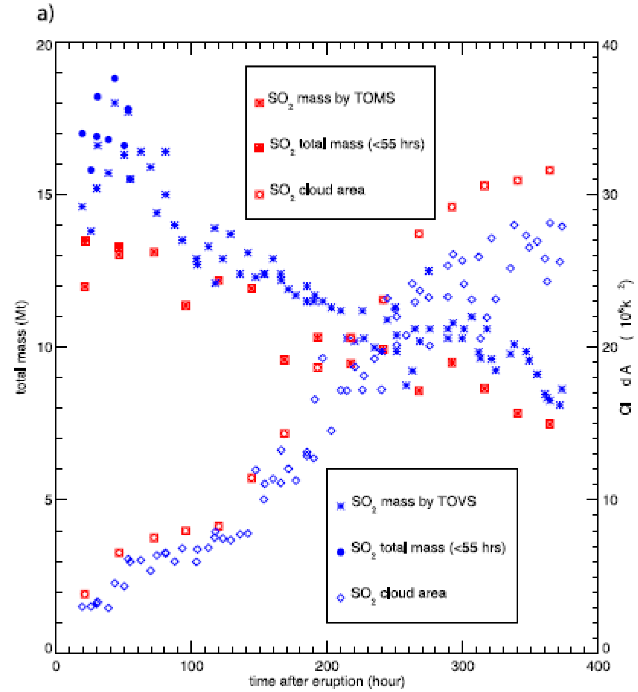
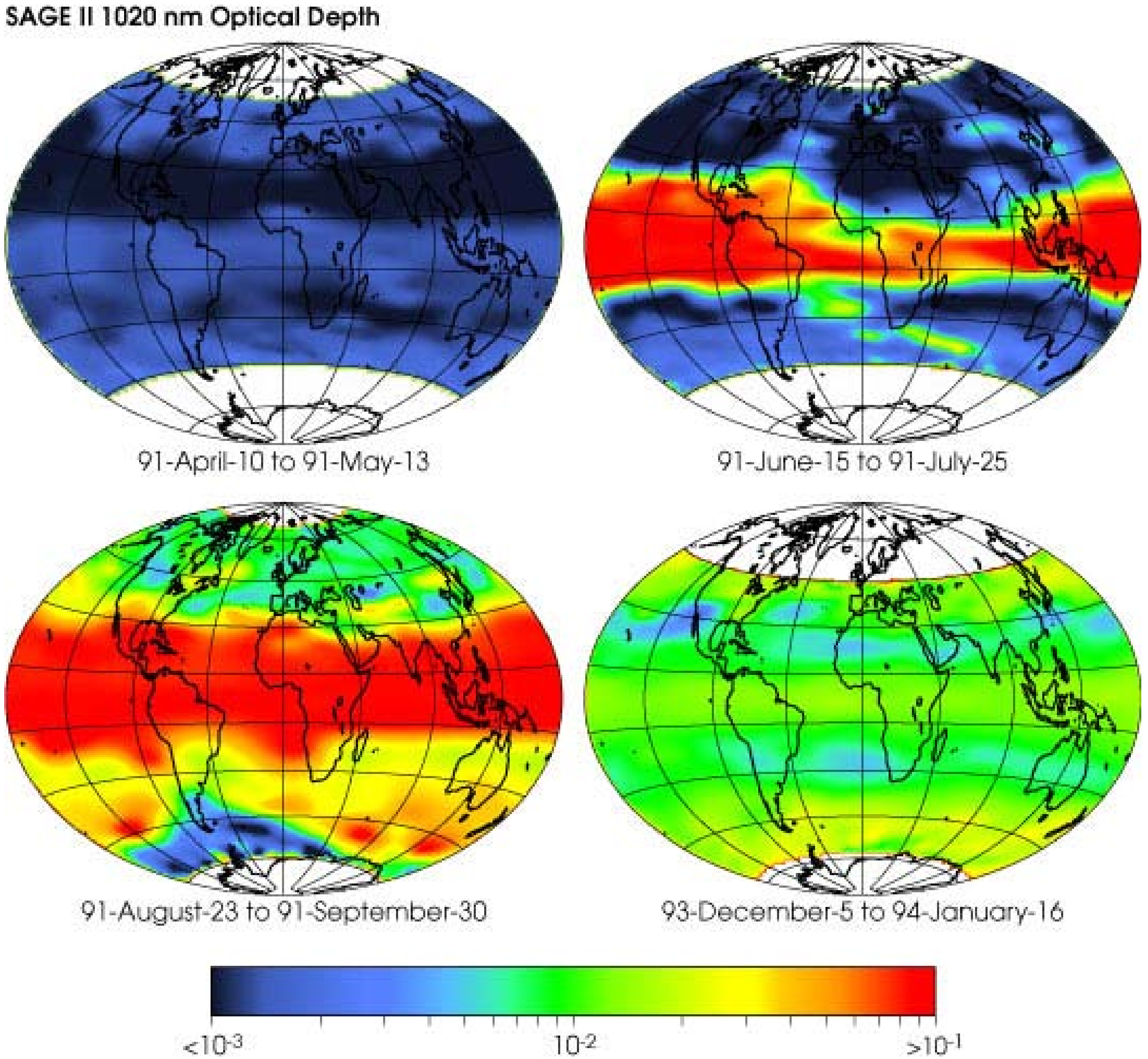


Figure 5. (a) SO_2 mass in Pinatubo cloud and cloud areas as a function of time after eruption, using TOMS and TOVS data (Table 2). SO_2 total masses represented by blue solid dots are the sum of SO_2 mass sensed by TOMS plus SO_2 mass sequestered by ice. (b) Burden of cloud (average mass/area) as a function of time after eruption using TOMS and TOVS data (Table 2).

Table 5. Summary of Results From This Paper and Previous Work

	This Paper		Previous Work		
Sensor	TOMS	TOVS	TOMS[a]	SBUV[b]	MLS[c]
Initial SO_2 mass (Mt)	18 ± 4[d]	19 ± 4[d]	20 ± 6	12–15	17[c]
SO_2 e-folding time (days)	25 ± 5	23 ± 5	35 ± 11	24 ± 5	33[c]

[a] *Bluth et al.* [1992].
[b] *McPeters* [1993].
[c] *Reed et al.* [1993], uncertainty unknown.
[d] Initially released SO_2 mass includes SO_2 sequestered in ice and SO_2 converted to sulfate during the rise of volcanic plume.


SAGE II 1020 nm Optical Depth
91-April-10 to 91-May-13
91-June-15 to 91-July-25
91-August-23 to 91-September-30
93-December-5 to 94-January-16
<10-3
10-2
>10-1

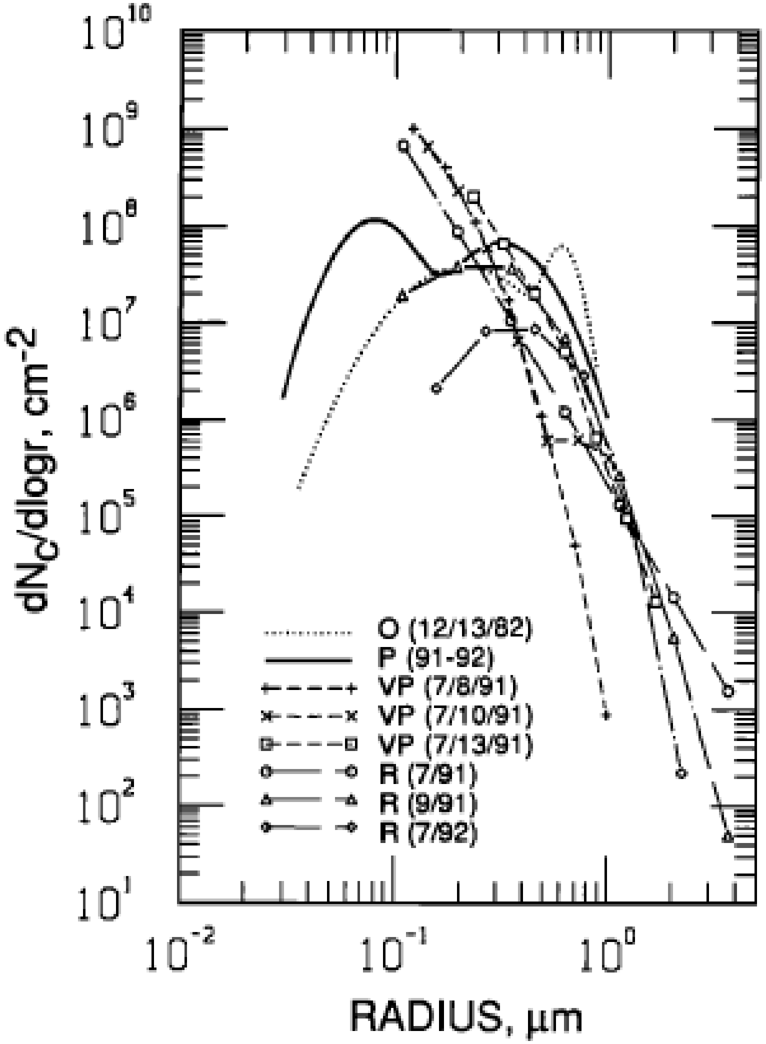


Fig. 8. Comparison of particle size distributions derived in the present work to previous measurements and models. O, *Oberbeck et al.* [1983]; P, *Pueschel et al.* [1992]; VP, *Valero and Pilewskie* [1992]; R, this work.

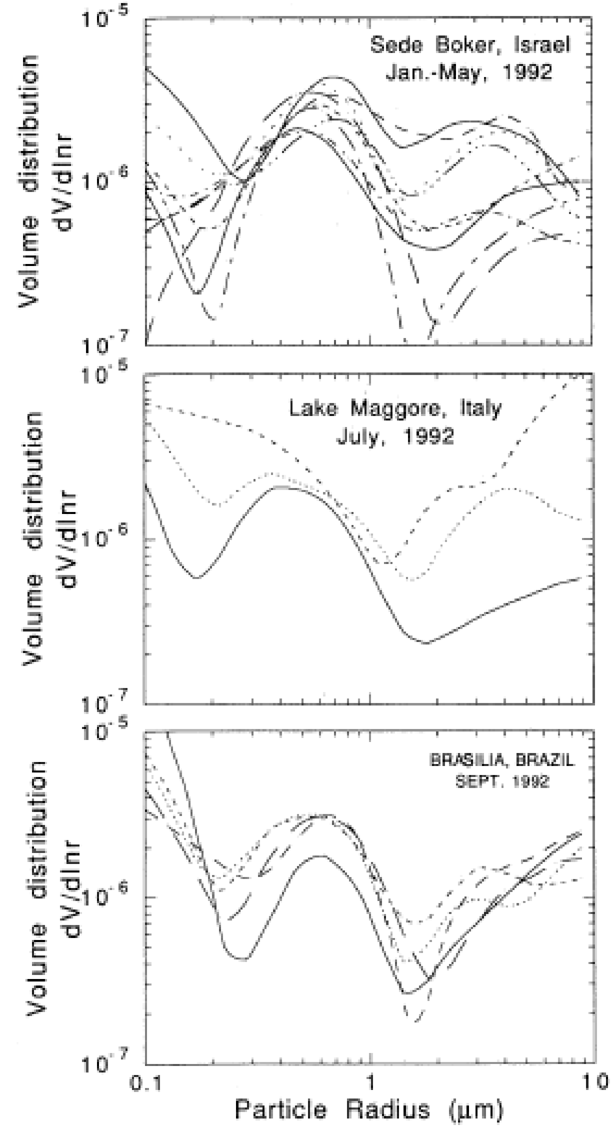
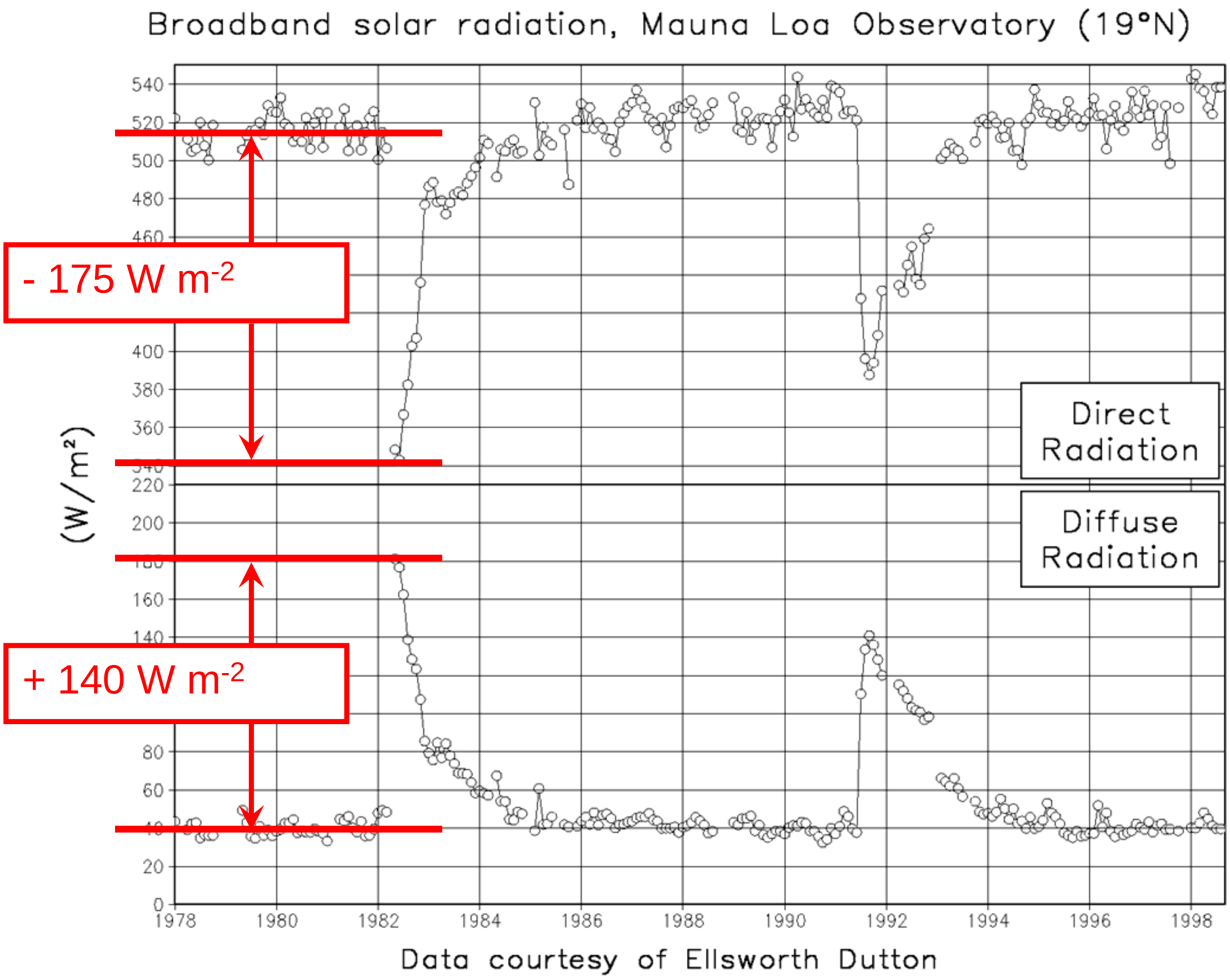


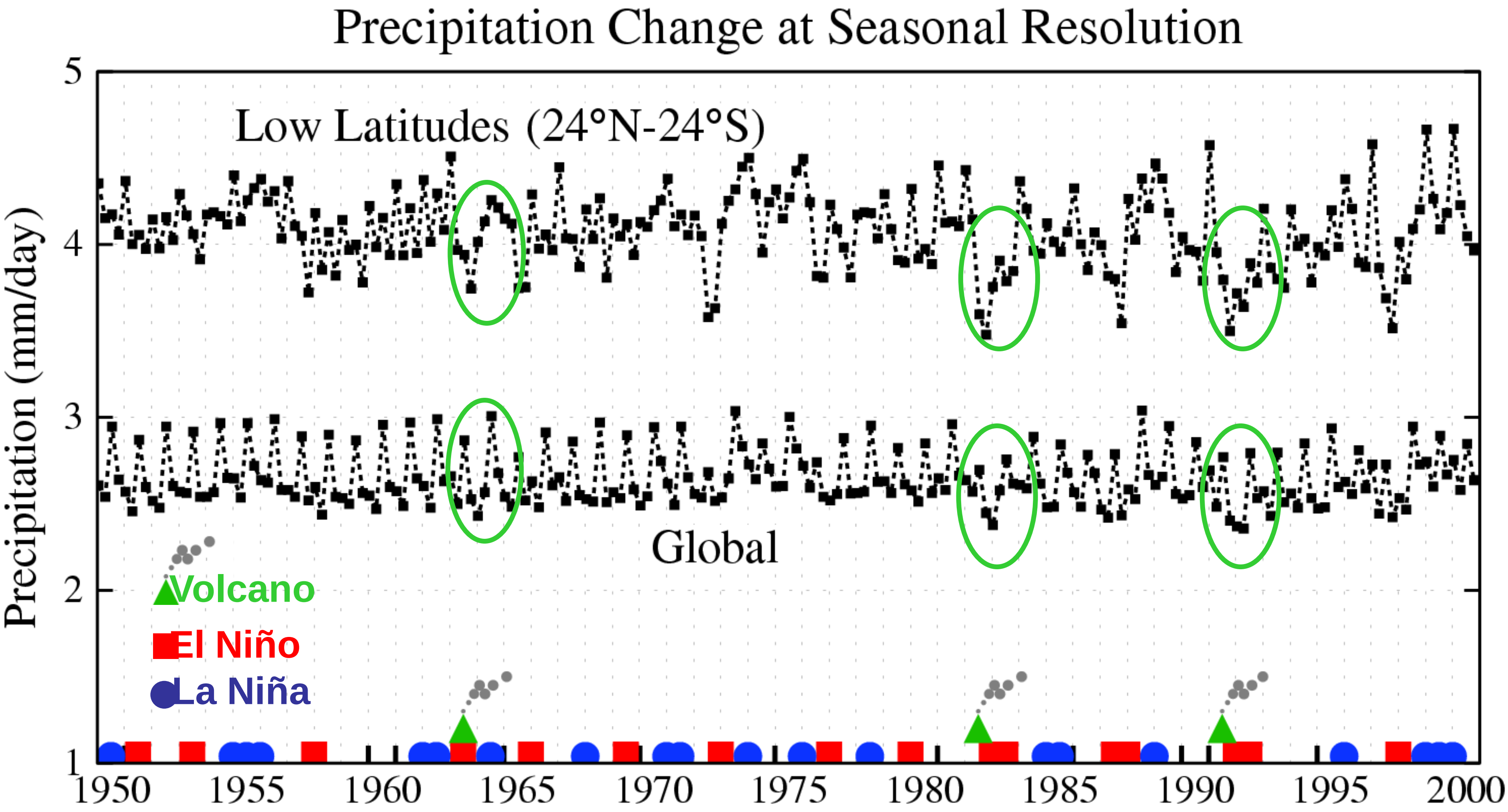
Figure 8. Individual size distributions derived from the almucantar measurements in Sede Boker, Israel (30.5°N, 34.7°E); Lake Maggore, Italy (45.5°N, 8.3°E); and Brasilia, Brazil (16.1°S, 44.3°W). The size distribution around the 0.5-μm radius shows the presence of the stratospheric aerosol.

Radiative effects



Robock (2000), Dutton and Bodhaine (2001)

Effects on precipitation



Drawn by Makiko Sato (NASA GISS) using CRU TS 2.0 data

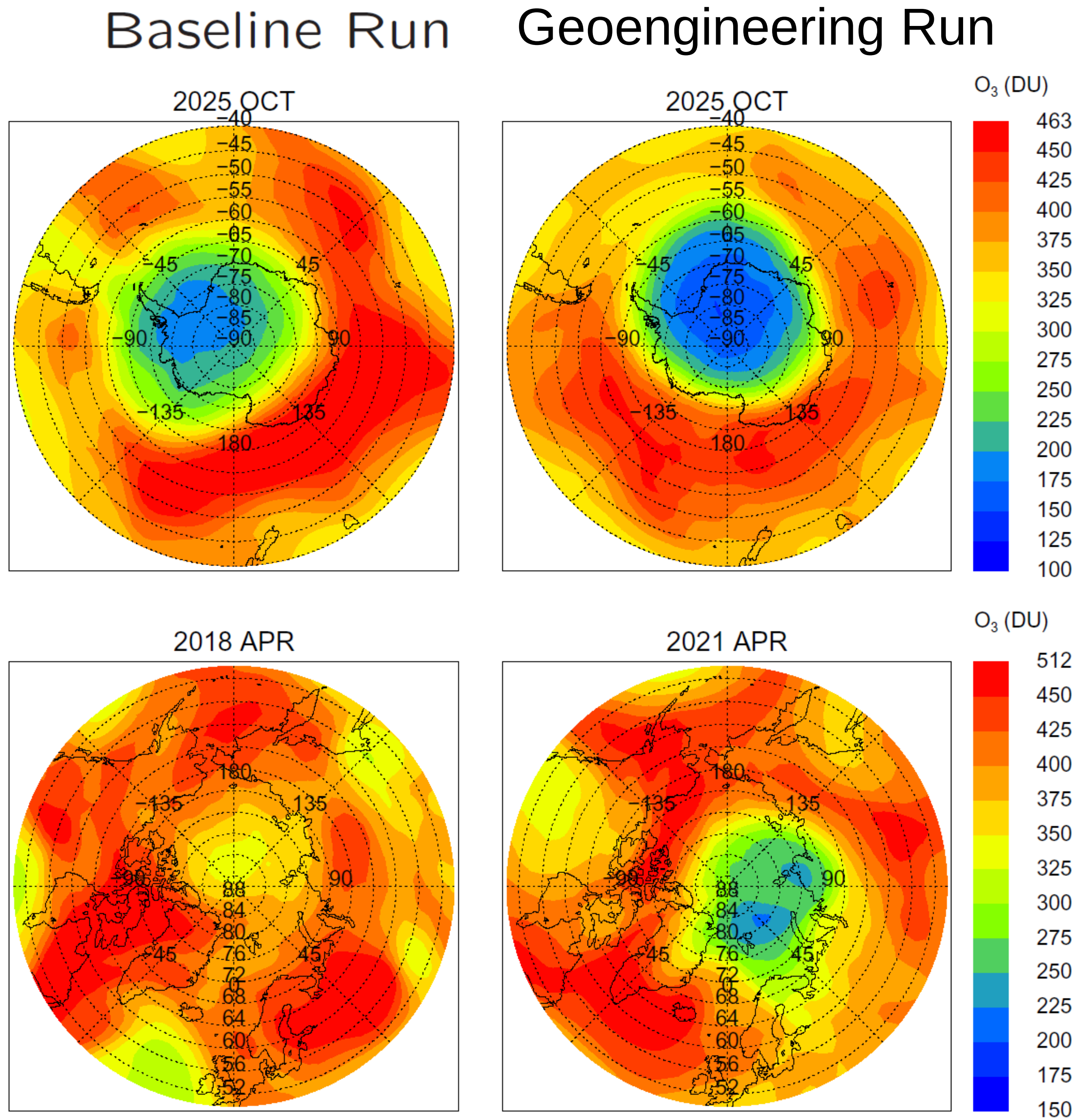
Effects on O_3

Rasch et al.(2008)

SH

Ozone concentration for coldest winters with and without geoengineering WACCM3 model runs by Tilmes et al. (2008) with 2 Tg S/yr

NH



SPICE

- Using volcanoes as natural analogues to investigate solar radiation management options for geoengineering
- Funded by a combination of EPRSC, NERC, and STFC through a sandpit in March 2010 - to Bristol, Cambridge, Oxford, Edinburgh, Met-office and RAL
- A sister project (IAGP) was also funded – PI: Piers Forster
- Close links between the two projects

Three overarching questions

- *How much*, of *what particles*, do we inject *where* into the stratosphere, for effective solar radiation management?
- *How* do we get them there?
- *What* are their effects on the environment?

Three workpackages

- WP1(Bristol) – particle candidates
  - Optical properties (RAL, Met. O)
  - Atmospheric impacts [O_3]
- WP2 (Cambridge) – delivery systems
  - Investigate delivery options
  - Plan for a 20 km tethered balloon/pipe system
  - Build 1 km engineering testbed
- WP3 (Oxford) – impacts
  - ‘Climate’ (HadGEM3)
  - Biosphere (LPX)

WP1.1 (particle optics)

- Molecular Spectroscopy Facility at RAL will be used to measure optical constants for a variety of natural and man-made particles over a 0.3-15 μm wavelength (Dan Peters, Don Grainger, AOPP; Kevin Smith, RAL)
- Dispersion is the key stumbling block – it is challenging to disperse the aerosol at the desired size (r_e = 0.2-0.5 microns)
- These measurements are directed by Mie scattering calculations (Don Grainger, Dan Peters AOPP)

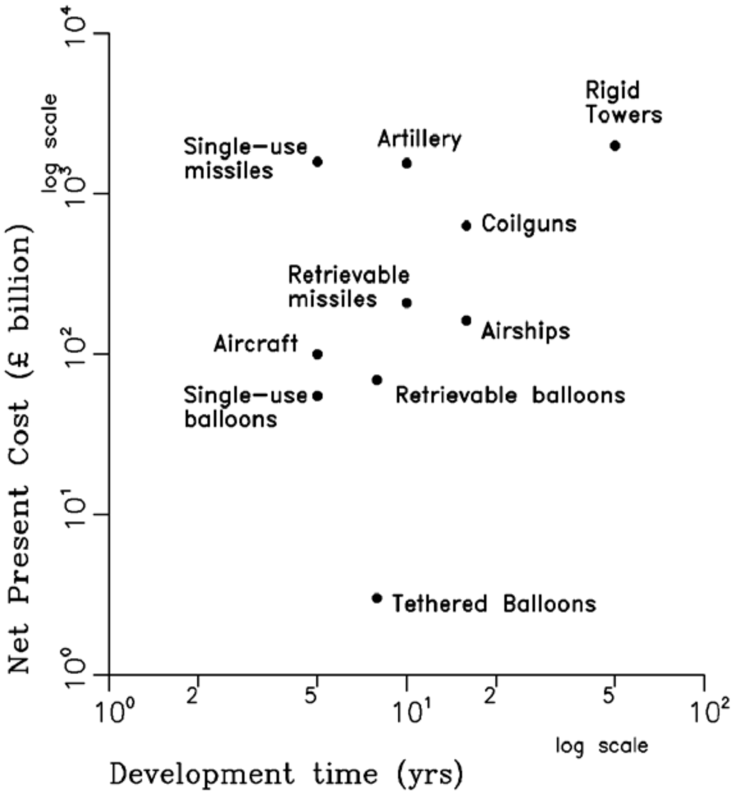
WP1.2 (effects on O_3)

- O_3 adsorption and uptake will be quantified using Chemical Ionisation Mass Spectroscopy (Pope, Cox, Kalberer) and BET (McGregor)
- At the Central Laser Facility (RAL) optical tweezers and raman spectroscopy will be used to probe the surface catalysis effects of the particle on O_3 (Francis Pope, Tony Cox, Cambridge ; Andy Ward, CLF)

WP2 - delivery

- Putting particles into the stratosphere (above 20 km) appears to be the cheapest, most effective option that can cool the earth quickly by ~ 2 degrees (Royal Society Report, 2009).
- Getting 1 to 10 million + tonnes pa particles to that altitude is very challenging.
- Main options considered are:
  - High performance military jets, ~ 1 million flights pa
  - Global array of weather balloons ~ 40 million flights pa
  - Pumping through pipes held aloft by large balloons,
    ~ 4 balloons of 280 m diameter

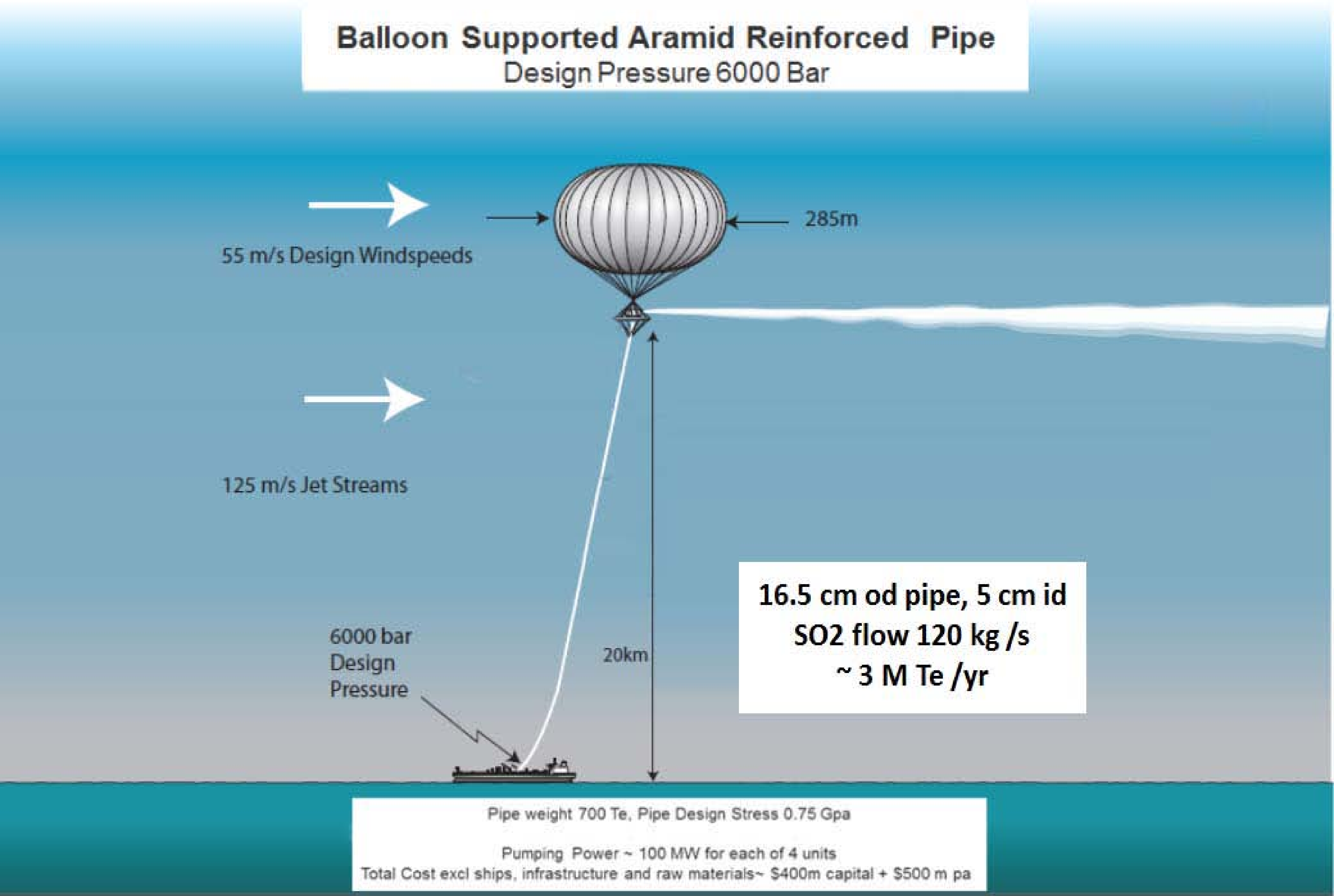
Delivery technology comparison



Davidson et al., sub judice

Technology	Initial Procurement Cost	Annual Operating Cost	Net present cost (£ billion)
Single-use Balloons	Facilities + Infrastructure	£7 billion	55
Retrievable Balloons	Facilities + Infrastructure + £1 billion	£9 billion	70
Tethered Balloons	Ships + £0.25 billion	400 MW pumping power = £350 million	3
Rigid Towers	£2,000 billion for 4 towers	400 MW pumping power	2003
50:50 Fast Jets / Tankers	Fleet of 500 fast jets + 65 tanker planes £17 billion	£11 billion	101
Artillery	460 guns = £1 billion + facilities + infrastructure	£204 billion	1576
Single-use Missiles	Low	£200 billion	1544
Retrievable Missiles	£20 billion	£25 billion	213
Coilguns	£2 billion	£80 billion	619
Airships	£80 billion	£11 billion	165

The Balloon / Pipe Technology



1/20 scale test bed

- Building a 1 km test bed is part of SPICE WP2
  - An engineering test, not a climate control test
  - Water/sea water only
  - Stagegated
- Will inform us about the tether, and pipe and balloon dynamics
- Will yield a better understanding of behaviour for the design of the 20 km pipe

WP3 impacts

- Looking at the impacts of large scale, long term injection, using Pinatubo as a benchmark
  - We still can’t model all the climatic effects of Pinatubo well
- Currently problems...
  - Ocean/atmosphere coupling
  - Stratospheric circulation and stratosphere/troposphere exchange

WP3 impacts

- Investigate (not limited to)
  - three primary climate markers - temperature, rainfall, O_3
- Explore the effects on the biosphere by altering the relationship between direct and diffuse incoming solar radiation
  - Global dynamic vegetation model (LPX)

Conclusions

- Mt. Pinabuto provided a large scale natural experiment that cooled global climate by ca. 0.5 K in June 1991

- SPICE is a large, complex, 3.5 year project involving six institutions and three research councils to investigate the feasibility of SRM