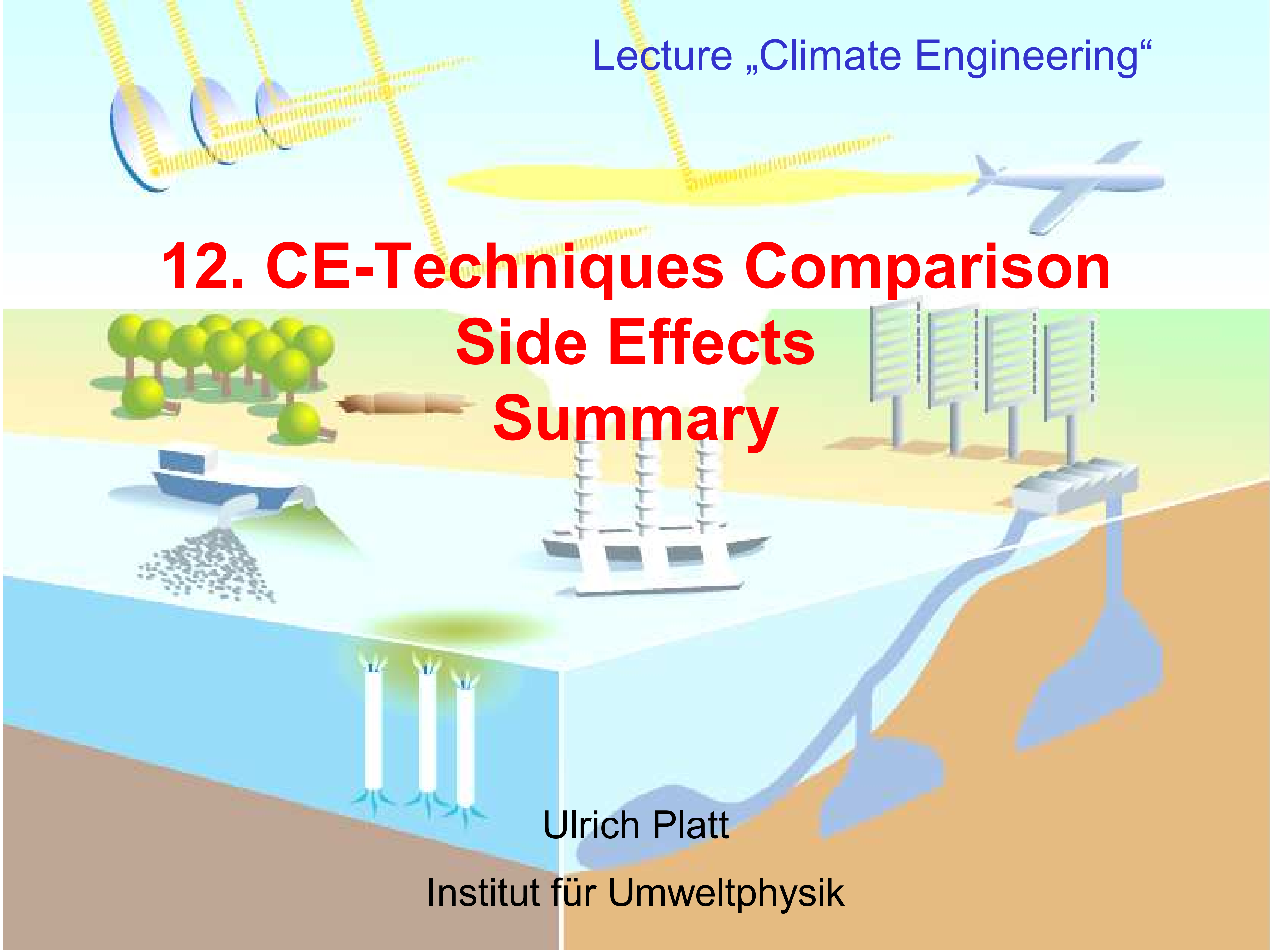
Lecture „Climate Engineering“

12. CE-Techniques Comparison
Side Effects
Summary



Ulrich Platt

Institut für Umweltphysik

Lecture Program of „Climate Engineering

Part 1: Introduction to the Climate System

1. Introduction and scope of the lecture
2. The Climate System – Radiation Balance
3. Elements of the Climate System - Greenhouse Gases, Clouds, Aerosol
4. Dynamics of the Climate System - Sensitivity, Predictions

Part 2: Climate Engineering Methods - Solar Radiation Management, SRM

1. SRM – Reflectors in space
2. SRM – Aerosol in the Stratosphere
3. SRM – Cloud Whitening
4. SRM – Anything else

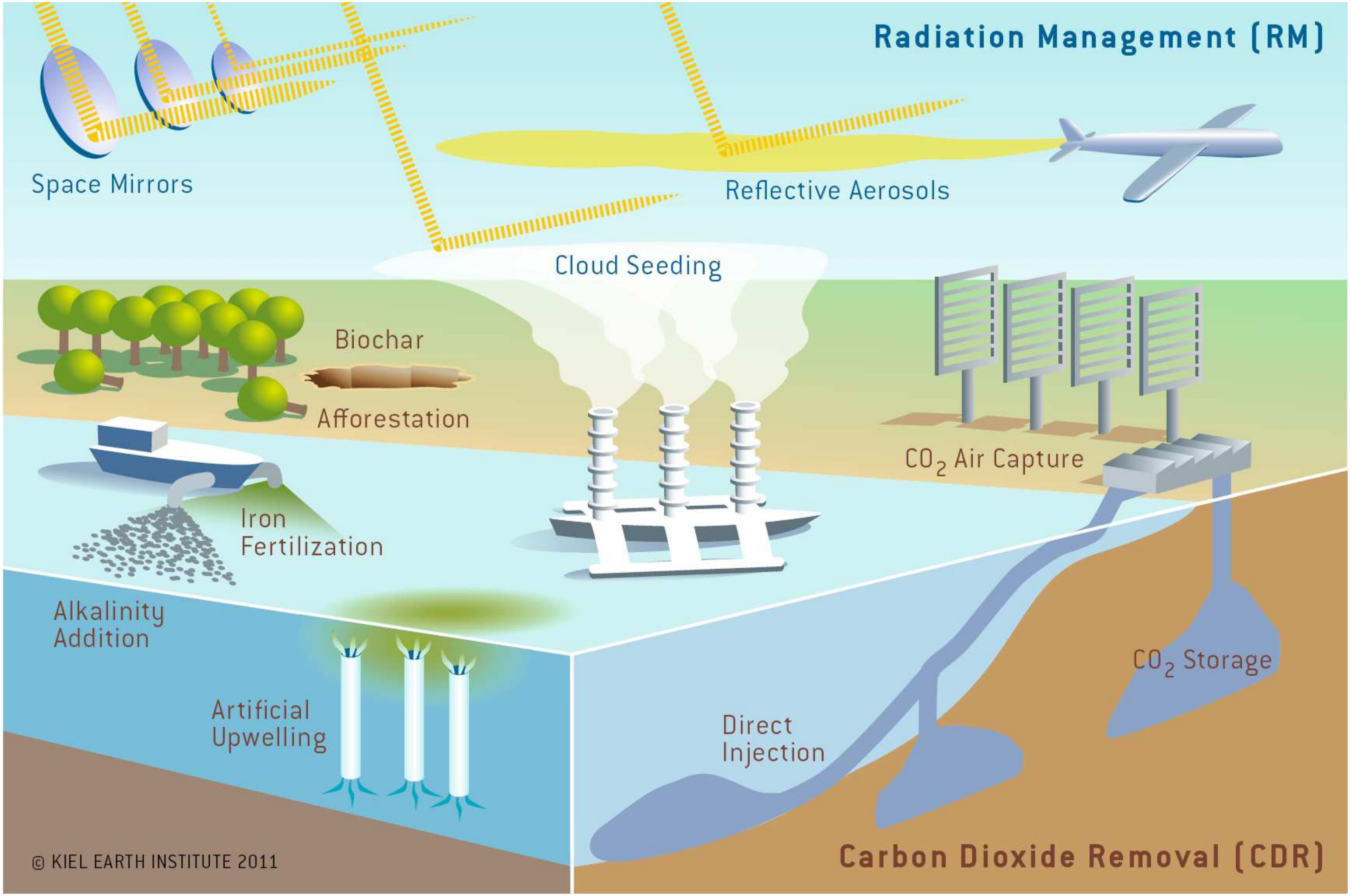
Part 3: Climate Engineering Methods – Carbon Dioxide Removal, CDR

1. Direct CO_2 removal (CDR) from air
2. Alkalinity to the ocean (enhanced weathering)
3. Ocean fertilization

Part 4: CE – Effectiveness, Side Effects

1. Comparison of Techniques, side effects, Summary

CE-Techniques



Contents of Today's Lecture

- Two basic types of CE-Techniques, reminder
- Why Climate Engineering?
- „Leverage“ Ratio of CE-Techniques
- How to test CE-Techniques
- CE-Governance
- Summary

Literature

Amelung D., Dietz W., Fernow H., Heyen D., Reichwein D., and Wiertz T. (2012), Beyond calculation - Climate Engineering risks from a social sciences perspective, Forum Marsilius-Kolleg 02, Heidelberg.

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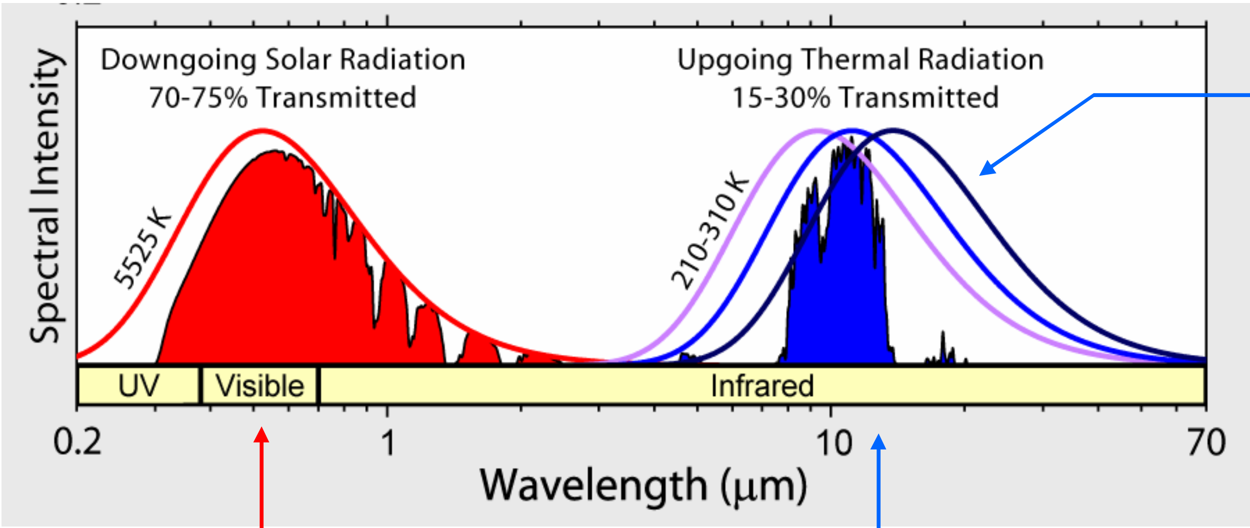
Two Types of „Climate Engineering“



Greenhouse gases reduce IR-emission

1) Solar radiation management (SRM)

- Sulfate aerosol in the stratosphere
- Cloud whitening
- Change surface albedo of Earth and/or ocean
- Special particles in the mesosphere
- Scatterers in space

Fast, cheap, imperfect and unsafe, little influence on atmospheric CO_2

2) Carbon cycle engineering (CDR)

- Direct capture of CO_2 from air
- Ocean fertilization
- Alkaline material into the ocean
- bury charcoal „Bio-char“
- Alkaline material into the soil

Slow and expensive,
But the cause (the CO_2) is actually removed from the air

Testing CE-Techniques

4 Levels of Tests:

1) Laboratory investigations and Modelling studies
   e.g.: Study of coagulation of sulfate particles, activities of CCN, dissolution of olivine powder ...
   → No environmental effects

2) Small-scale field studies
   e.g. Transport of SO_2 to the stratosphere, monitoring conversion time to sulfate particles, monitoring cloud seeding, Fe-fertilization experiments
   → No or negligible environmental effects

3) Large scale field studies
   e.g. Verifying that cloud seeding actually enhances cloud albedo on a large scale, studying change of circulation due to cloud seeding
   → Noticeable environmental effects

4) Test application of a (nearly) global scale
   only these tests will give certainty that the CE-measures actually work and what the side effects are
   → Severe (intended) environmental effects

How to Test Climate Engineering Measures?

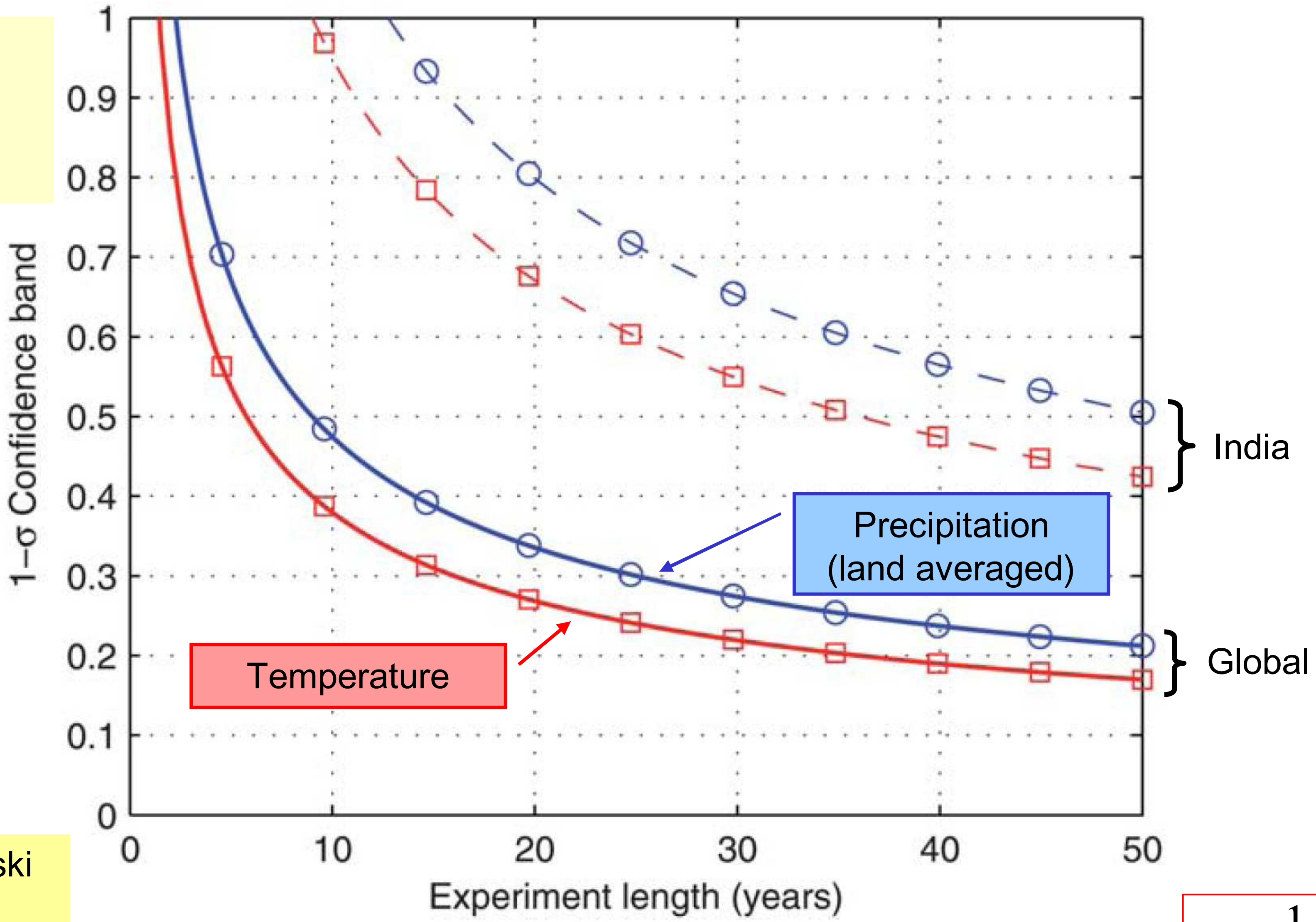
The Role of Field Trials

Sooner or later, the improvement of our understanding of CE technologies will necessitate large-scale field trials that come very close to an actual application of the technologies.
Such field trials should be accompanied by comprehensive monitoring programs.
Even if we assume the best possible design for large-scale trials, unequivocal identification and quantification of the effects and side-effects of particular technologies would take many years or even decades.
In the course of a field trial extending over such a long period, apparent effects and side-effects unrelated to the application of the technology would also occur.

The conduct of such a large-scale trial without the occurrence of significant social and political impacts must be considered one of the major challenges of climate engineering.

Testability of CE-Measures (SRM)

Accuracy in units of temperature variability

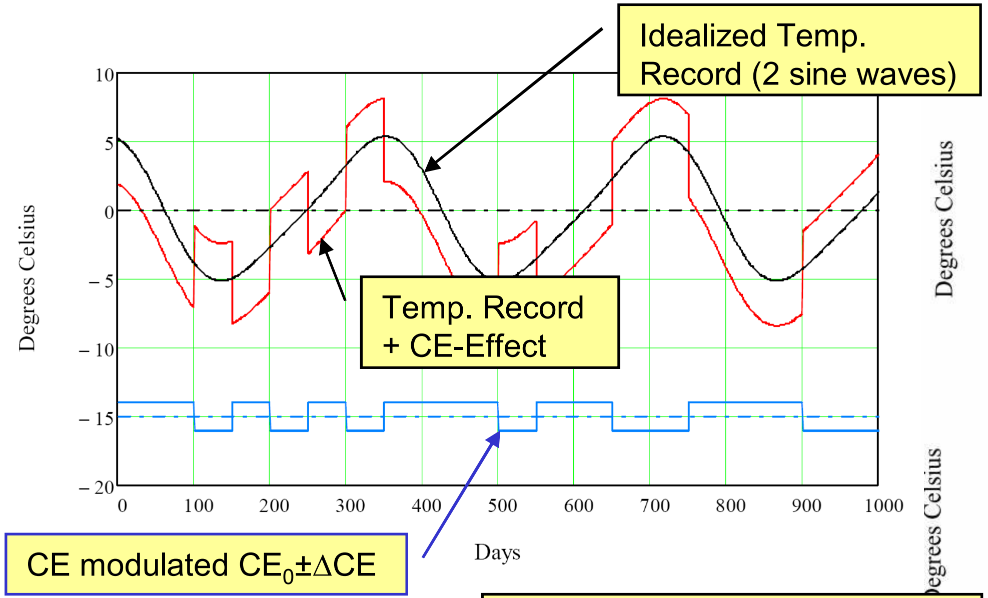


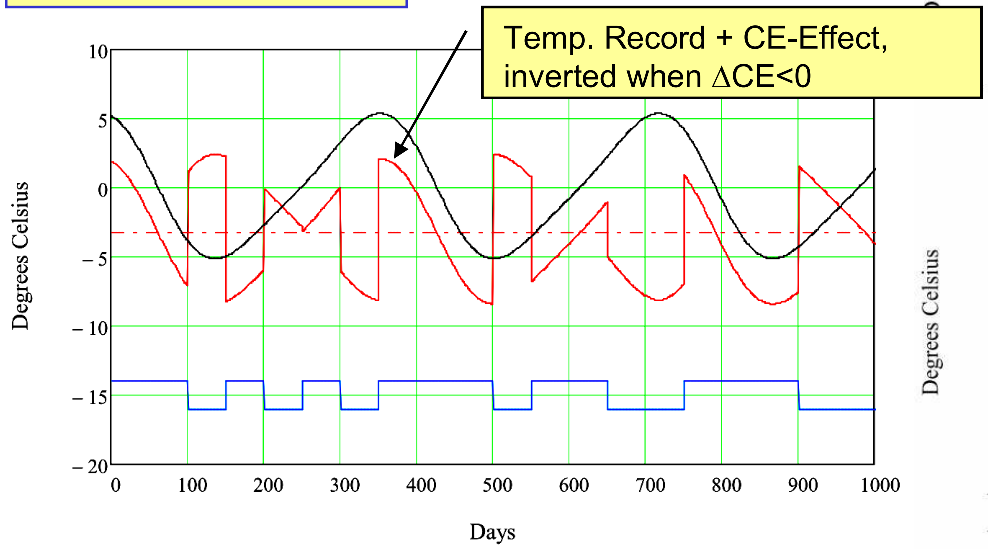
MacMynowski et al. 2011

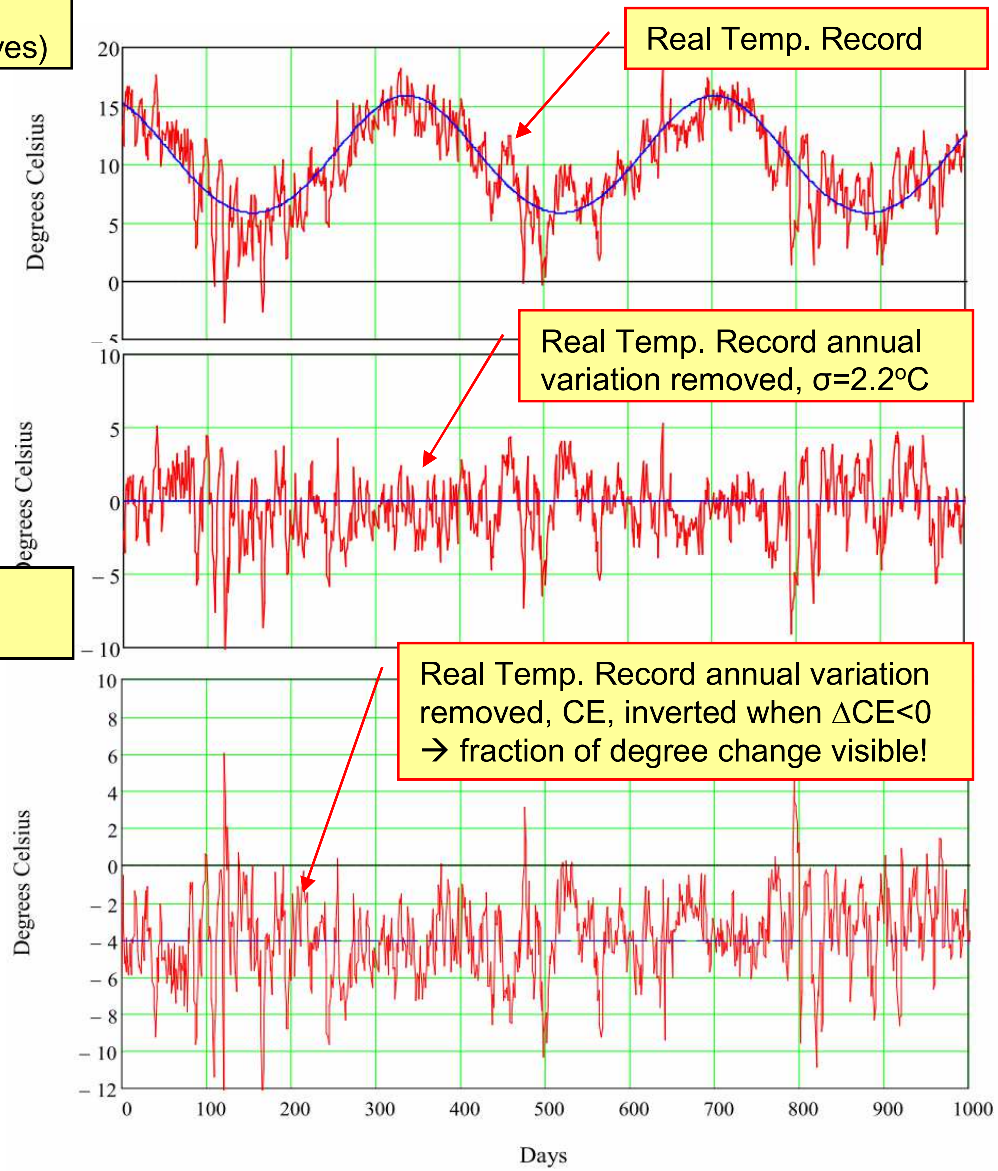
$$t \propto \frac{1}{\sqrt{F}}$$

Testing time t required to achieve a specified accuracy in estimating the response to SRM forcing (standard deviation, normalized by the estimate) for F = 1 W/m^2 forcing;

Testability of CE-Measures: Salter‘s Idea – Pseudo Random Variation of CE



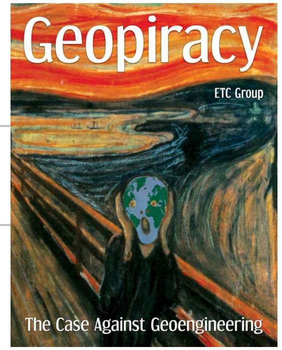




Salter S. (2010) Pseudo-random Spray Patterns for aWorld-Wide Transfer-Function of Cloud Albedo Control for the Reversal of Global Warming.

The Geoengineering World Map

(Are we already testing CE?)



Geoengineering Earth System Experimentation

http://www.etcgroup.org/issues/climate-geoengineering

Geoengineering Hotspots | Some reported activity | No reported activity

Increased precipitation | Reduced precipitation | Air capture | Solar radiation management | Ocean fertilization

SOURCE: ETCGROUP.ORG

http://www.guardian.co.uk/environment/graphic/2012/jul/17/geoengineering-world-map

The „Leverage“ of CE - Techniques

Leverage Ratio:

$$R_{Lev} = \frac{Mass\ of\ Greenhouse\ Gas\ the\ effect\ of\ which\ is\ neutralized}{Mass\ of\ material\ needed\ for\ the\ measure}$$

Examples:

1) Mankind emitted about 370 Gt carbon (1357 Gt CO_2) since 1750. About 1 Mt of sulfur would be required to offset the warming effect of that much CO_2 (for one year)
→ $R_{lev} \approx 1.4 \cdot 10^6$/year

2) In order to induce ocean uptake of the same amount of CO_2 about 3100 Gt of $CaCO_3$ (carbonate) would be required
→ $R_{lev} \approx 0.44$

($CO_2 + CaCO_3 + H_2O \rightarrow Ca(HCO_3)_2$)

3) Iron Fertilization of the ocean requires ≈1 atom of Fe for 10^5 atoms of C in algal biomass (Redfield ratio) → mass ratio $R_{lev} \approx 2.5 \cdot 10^4$

Overview of CE-Measures

Type of CE-Measure	Technology	Method	Anticipated Potential	Leverage Factor	Decay Time
Symptomatic: Modification of Radiation Budget (RM)	Reflectors in Space	Reduction of the short-wave Irradiation (SRM)	Unlimited	$\approx 10^4$ year^{-1}	Decades to Millennia
	Aerosol in the Stratosphere	Reduction of the short-wave Irradiation (SRM)	-2 to -4 W/m^2 (10 MtS/year)	(1-3)·10^5 year^{-1}	≈ 1 Year
	Modification of Cirrus Clouds	Increase of long-wave Emission (TRM)	-1 ... -2.8 W/m^2	$\approx 10^3$ year^{-1}	Days to Weeks
	Modification of Marine Stratiform Clouds	Reduction of the short-wave Irradiation (SRM)	-4 W/m^2	$\approx 10^3$ year^{-1}	Days
	Modification of the Earth's Surface - Albedo	Reduction of the short-wave Irradiation (SRM)	-0.2 to -3 W/m^2	?	Years to Decades
Removing the cause: Reduction of the concentration of IR-absorbing atmospheric components (CDR)	Physical / Ocean	Artificial upwelling	?	?	-
	Chemical / Ocean	Dump carbonate or silicates (Olivine) into the ocean	≈ 1 GtC/Year	≈ 1	-
	Biological / Ocean	Ocean Fertilization (Iron, Phosphorus, …)	<1 GtC/Year	10^2 to < 10^5	-
	Biological / Land	Photosynthetic fixation as organic Carbon (afforestation, burial of charcoal)	≈ 5 GtC/Year	≈ 1	-
	Chemical / Land	Artificial Weathering and Air Capture Techniques		≈ 1	-

Leverage Ratio of Stratospheric Aerosol - CE

Remember:

$$R_{Lev} = \frac{\textit{Mass of Greenhouse Gas the effect of which is neutralized}}{\textit{Mass of material needed for the measure}}$$

Assuming that **10 MtS/year** can reduce the forcing by ≈ 4 W/m² (optimistic)

→ This would approximately cancle the effect of CO_2-doubling (from 280 ppm pre-industrial to 560 ppm, actually 3.7 W/m²).

Mass of 280 ppm of atmospheric CO_2:

$$M_{CO2}(1\,\text{ppm}) = \frac{M_{CO2}}{\overline{M}_{Air}} \cdot 10^{-6} \cdot M_{Atm}$$

$$M_{Atm} = \frac{\overline{P}_{Atm} \cdot A_{Earth}}{g} \approx \frac{1.01325\,\text{Pa} \cdot 5.1 \cdot 10^{14}\text{m}^2}{9.81\,\text{N/kg}} \approx 5.266 \cdot 10^{18}\,\text{kg}$$

$$M_{CO2}(1\,\text{ppm}) \approx \frac{44}{29} \cdot 10^{-6} \cdot 5.266 \cdot 10^{18}\,\text{kg} \approx 7.99 \cdot 10^{12}\,\text{kg} \approx 8\,\text{Gt}$$

$$M_{CO2}(280\,\text{ppm}) \approx 2237\,\text{Gt CO}_2\ (610\,\text{GtC})$$

→

$$R_{Lev} = \frac{2237\,Gt}{10\,Mt} \approx 2.24 \cdot 10^5\ \textit{per year}$$

Leverage Factor for Space Reflectors

We assume 10^8 t of reflector weight for counteracting 3.7 W/m^2
(CO_2 – doubling, from 280 ppm pre-industrial to 560 ppm)
CO_2-Mass (additional 280 ppm): 2237 Gt

Including mass of rockets for launch from Earth: 100 – times larger

→ 10^{10} t

Assumed Lifetime: 100 years

→ 10^8 t/year or 100 Mt/year

$$R_{Lev} = \frac{2237\,Gt}{100\,Mt} \approx 2.24 \cdot 10^4 \; per\; year$$

Leverage Factor for Cloud Whitening

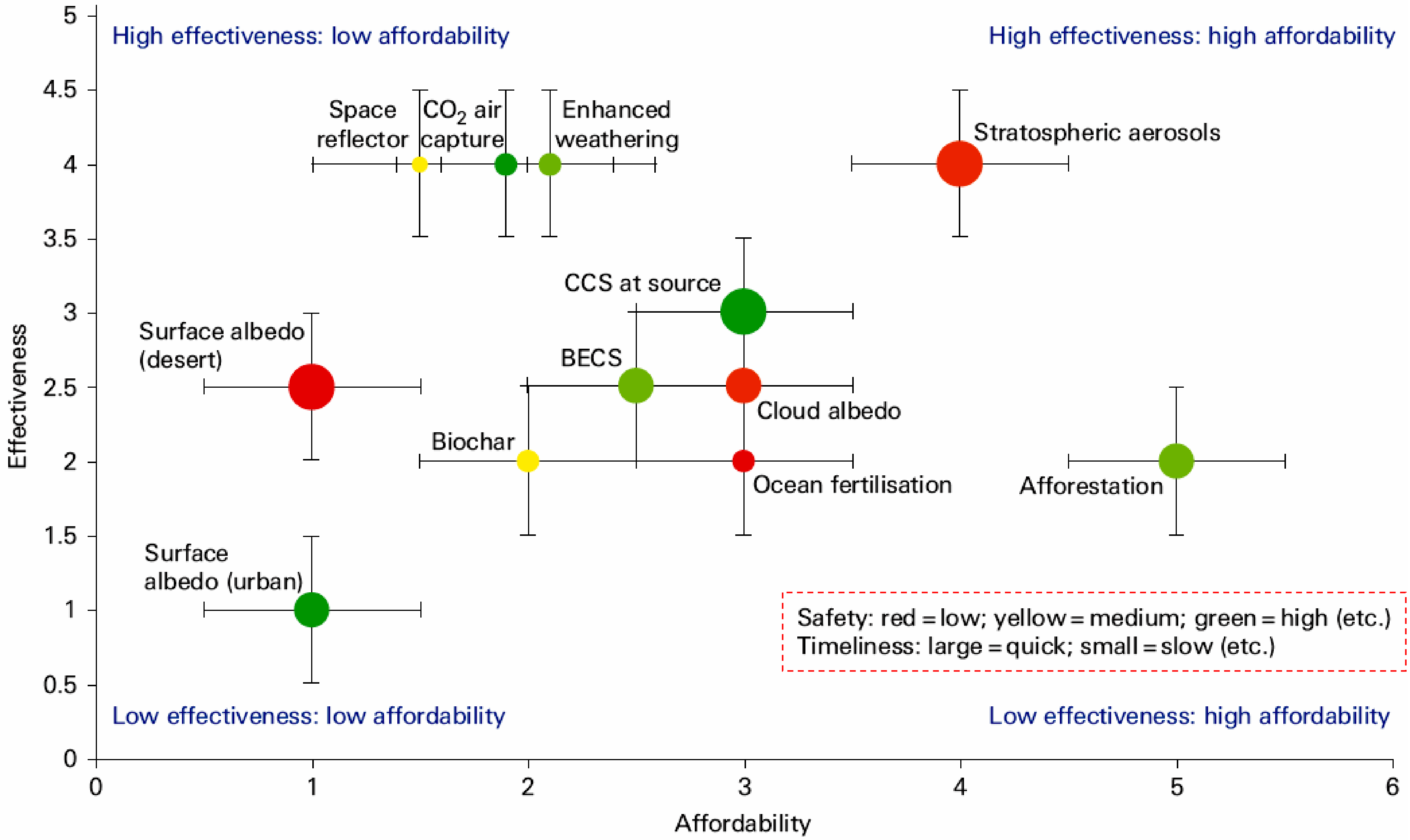
We assume 10^{10} kg (10^7 t) of sea water per 3 days for counteracting 3.7 W/m^2 (CO_2 – doubling, from 280 ppm pre-industrial to 560 ppm)
CO_2-Mass (additional 280 ppm): 2237 Gt

→ $\approx 10^9$ t / year (1Gt/year)

Leverage Factor:

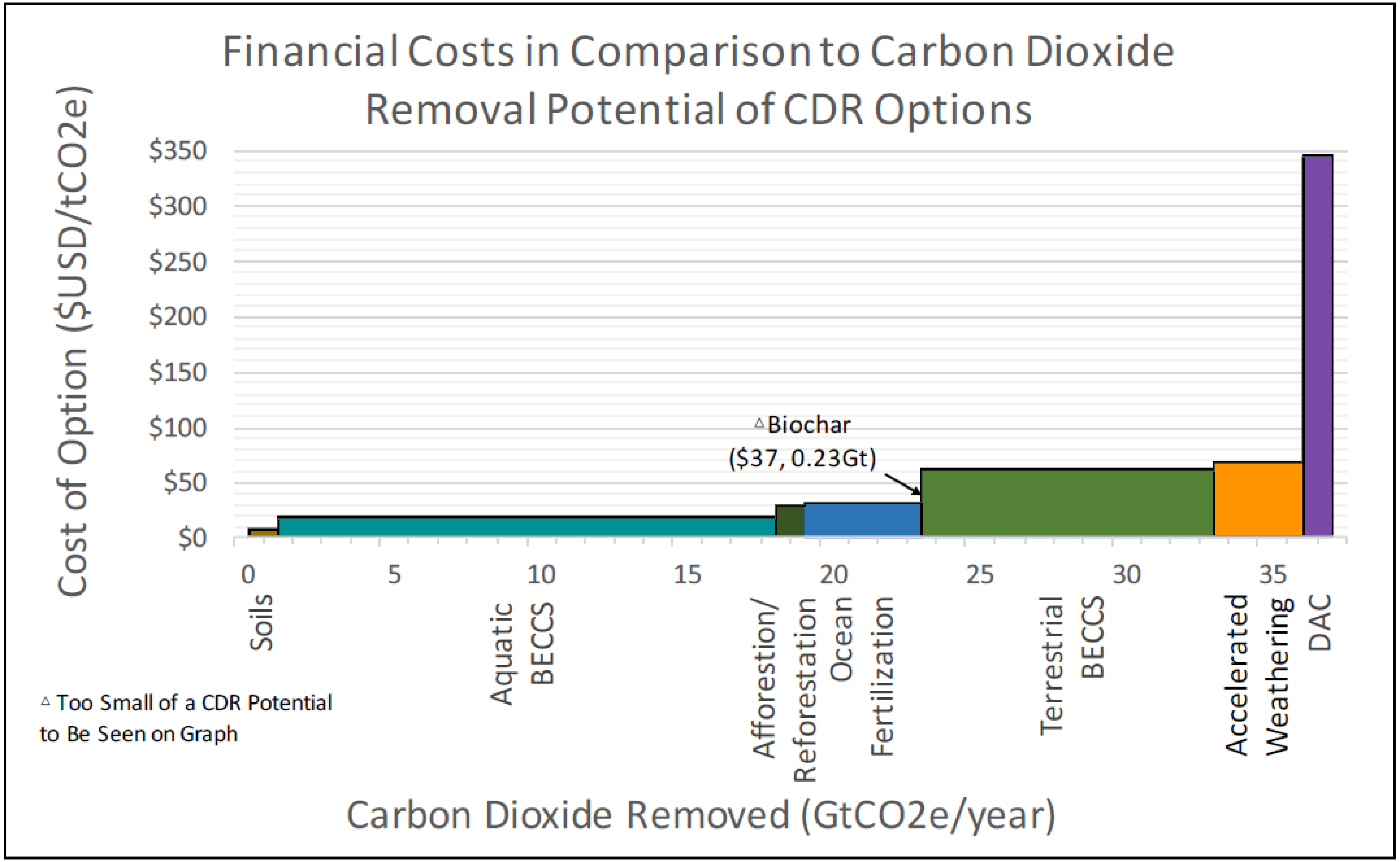
$$R_{Lev} = \frac{2237\,Gt}{1\,Gt} \approx 2.24 \cdot 10^3 \ per\ year$$

Efficiency – Cost – Safety - Timeliness of CE-Measures



source: Geoengineering the climate: Science, Governance and Uncertainty, The Royal Society, 2009

Estimated Cost of Different CDR-Techniques



D. Martin, K. Johnson, A. Stolberg, X. Zhang, C. De Young (2017), **Carbon Dioxide Removal Options: A Literature Review Identifying Carbon Removal Potentials and Costs**, Master of Science Project (Natural Resources and Environment) University of Michigan, USA

Limitation of CE-Measures

Most CE-measures are just barely able to counteract the effect of e.g. a doubling of atmospheric CO_2:

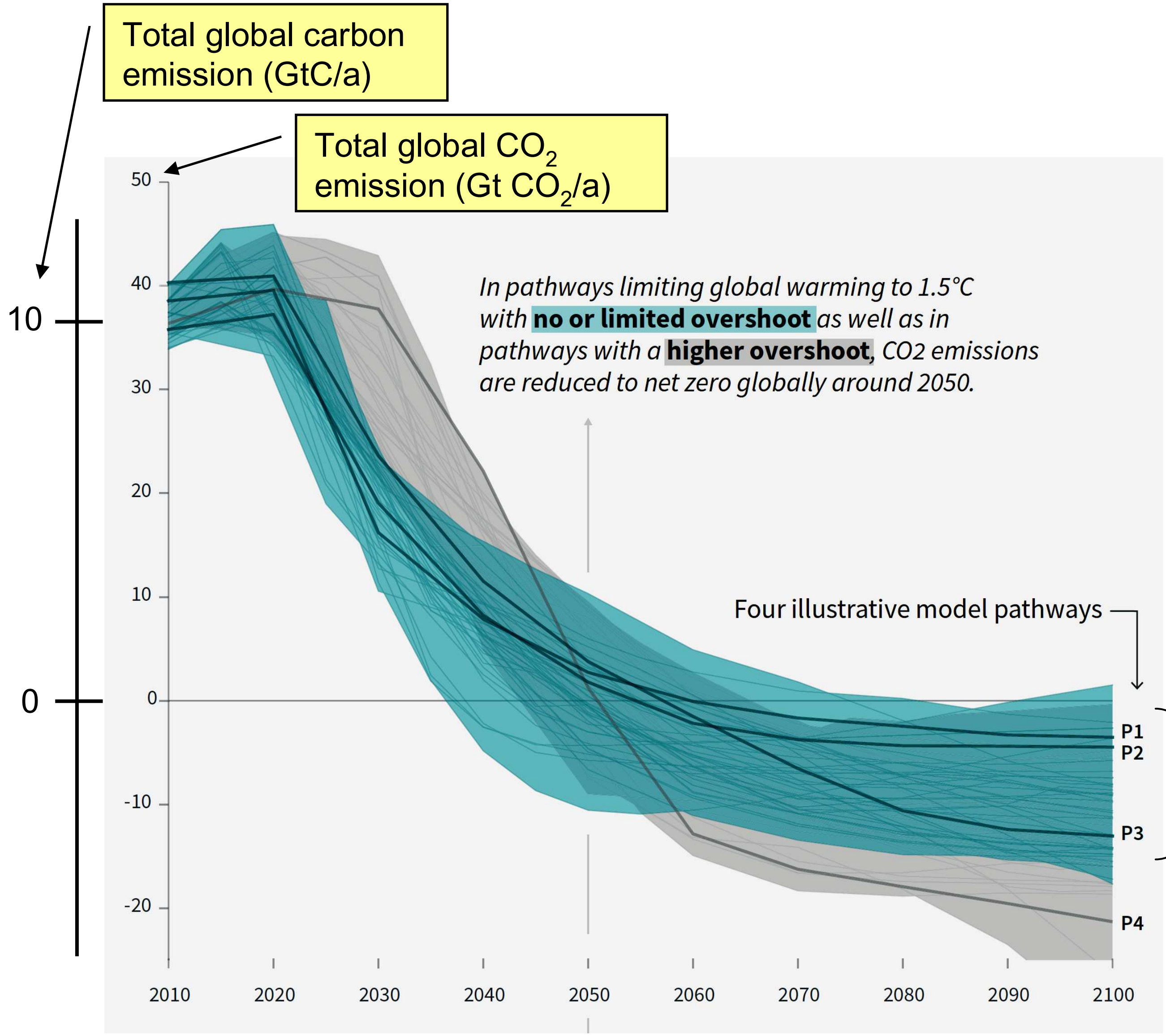
- With the exception of reflectors in space SRM measures can probably at most provide a negative radiative of 4 W/m^2.
- Likewise most CDR measures (in particular ocean liming) can remove no more than about 1 GtC/year (3.7 Gt CO_2/year) and thus compensate only around 10% of the annual anthropogenic CO_2 – emission

→ A combination of measures may be needed or CE can only be supporting other measures (like mitigation)

Questions beyound Technological Feasibility and Cost of CE-Measures

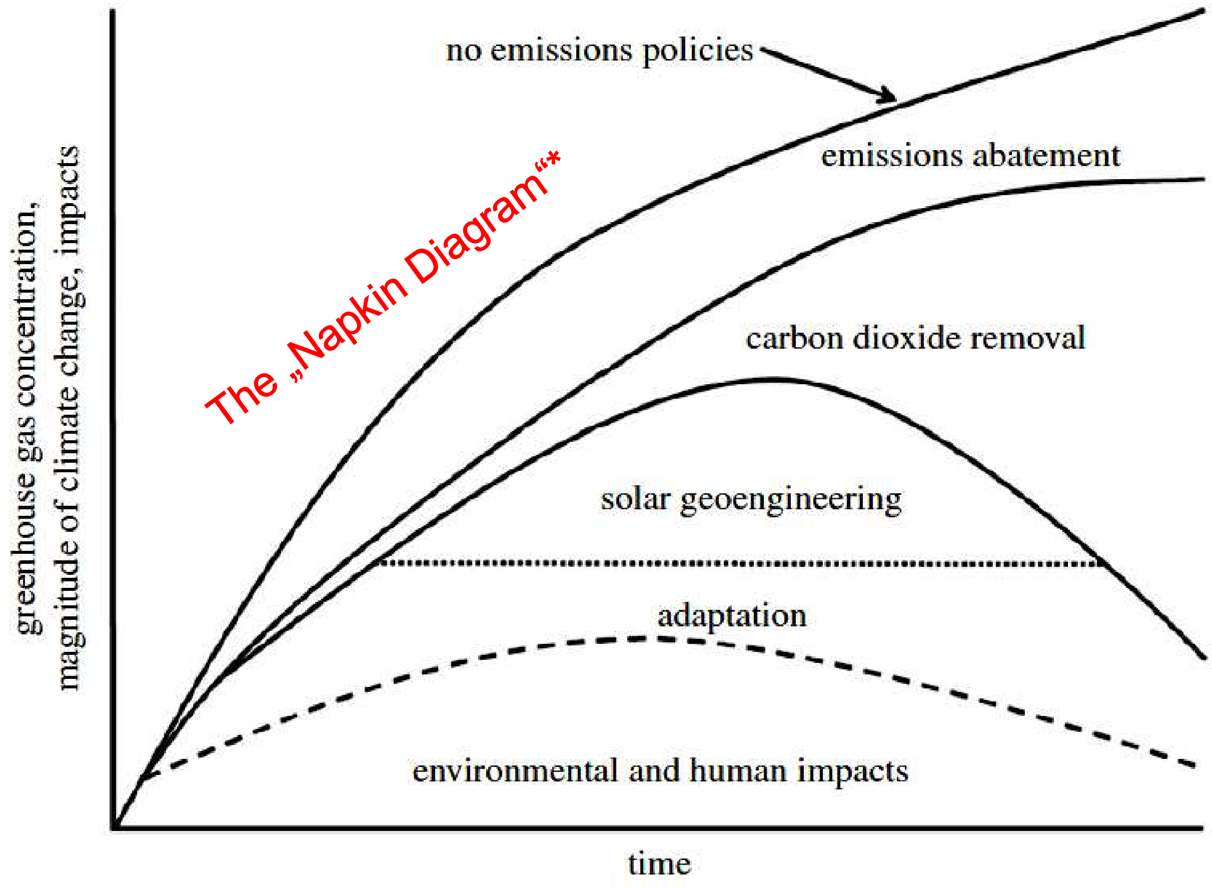
- CE in only cases of severe emergency (Crutzen)?
- CE could be used to „buy time“ for mitigation or adaptation
- CE could give a feeling of false scurity (we continue as usual, apply CE if there should be a problem), „moral hazard“
- CE could be used as excuse for neglecting mitigation and adapatation?
- Some CE-measures appear to be very cheap in comparison to mitigation → Danger of unilateral application?
- Ethics of CE?
- Legal questions (precautionary principle, compensation for damages)
- Political enforceability?
- Who can guarantee the continuation of CE-measures over centuries (or millennia)?
- Who decides on termination or continuation of CE – measures in case of problems?
- What happens if CE-measures are (or have to be) terminated?

IPCC-Special Report on the 1.5 Degree Goal



All scenarios (pathways) which are predicted to meet the 1.5o goal include ‚net negative emissions' i.e. some kind of CO_2-removal from the atmosphere.

Scenario where we could need Climate Engineering?



Source: Reynolds J.L. (2019), Solar geoengineering to reduce climate change: a review of governance proposals. *Proc. R. Soc. A* 475: 20190255.

*Long J.C.S. & Shepherd J.G. (2014), The strategic value of geoengineering research. In Global environmental change, Ed. B. Freedman, 757–770. Dordrecht, The Netherlands: Springer.

Ideal complementary roles of responses to climate change:

- Emissions abatement: slow and cannot reduce greenhouse gas concentrations over time.
- CDR: also slow but can reduce them over time.
- Solar geoengineering no effect on greenhouse gas conc., but could rapidly reduce climate change, thus ‘shaving the peak’ of dangerous climate change.
- Adaptation does not affect climate change but can reduce impacts.

Ethics of CE (Royal Society)

Decisions to deliberately modify the Earth's climate undoubtedly raise a number of different ethical issues. To explore these, the Royal Society invited a panel of ethicists to consider three questions (Annex 8.3).

1. Would deliberate geoengineering be unethical and are some geoengineering techniques more ethically acceptable than others - if so, which and why?
2. Is a higher standard of proof or confidence needed for geoengineering interventions than for other mitigation actions?
3. What are the main ethical considerations that the design of a regulatory framework for geoengineering research or deployment would need to take into account?

Three main ethical positions were identified in relation to geoengineering, including:

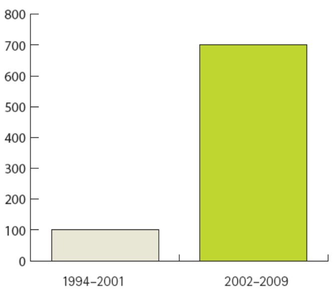
- *consequentialist*, in which the value of outcomes is the predominant consideration;
- *deontological*, where the primary consideration is the issue of duty and 'right behaviour' (with less interest in outcomes);
- *virtue-based*, concerned primarily in this context with dilemmas of hubris and arrogance.

Concerned Voices

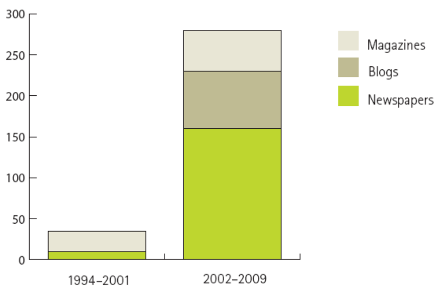
Rich, panicky governments are hoping for quick fixes rather than risk inconveniencing their electorate or offending industry. As dangerous as geoengineering may sound (and turn out to be), governments around the world are aware that some action must be taken quickly. They're also aware that carbon-trading schemes won't put a dent in climate change. Geoengineering warrants serious debate and preemptive action.

"If we could come up with a geoengineering answer to this problem, then Copenhagen wouldn't be necessary. We could carry on flying our planes and driving our cars."
Sir Richard Branson, industrialist and airline owner

Scientific Articles on Geoengineering before and after 2002



Media Coverage of Geoengineering Articles before and after 2002



http://www.etcgroup.org/issues/climate-geoengineering

Arguments Against CE

1. There is considerable uncertainty about the side-effects of the different technologies

2. Terminating CE technologies may result in far worse climate change,

3. Only a partial offsetting of anthropogenic climate change can be achieved (for most CE techniques)

4. Considerable distributional effects and corresponding social and geopolitical conflict may arise from the various regional effects

5. Conventional emission control efforts will slacken.

6. There are fundamental objections based on normative attitudes (e.g., arguments that are religious or based on deep-rooted criticism of civilization, as such).

→ The climate engineering debate tends to be rather adversarial and is no longer limited to the question of scientific feasibility or the efficiency of the technologies involved.

Arguments in Favour of CE

1. In the event of high climate sensitivity the consequences of climate change may be greater than previously estimated

2. The progress of international negotiations on emission control tends to be too slow

3. Even on a long timescale the warming that has already occurred may be irreversible

4. Exceeding critical thresholds in the climate system may trigger disastrous damage.

With this in mind, advocates of climate engineering argue that these technologies could represent a necessary (emergency) option in counteracting climate change.

BMBF-Report 2012

Unilateral Geoengineering

Non-technical Briefing Notes for a Workshop
At the Council on Foreign Relations
Washington DC, May 05, 2008

Katharine Ricke, M. Granger Morgan and Jay Apt, Carnegie Mellon
David Victor, Stanford
John Steinbruner, University of Maryland

Unlike the control of greenhouse gas emissions, which must be undertaken by all major emitting nations to be effective and is likely to be costly, geoengineering could be undertaken quickly and unilaterally by a single party, at relatively low cost. Unilateral geoengineering, however, is highly likely to impose costs on other countries and run risks with the entire planet's climate system.

Key Recommendations of the Royal Society (2009)

- Geoengineering methods of both types should only be considered as part of a wider package of options for addressing climate change. CDR methods should be regarded as preferable to SRM methods as a way to augment continuing mitigation action in the long term. However SRM methods may provide a potentially useful short-term backup to mitigation in case rapid reductions in global temperatures are needed;

- CDR methods that have been demonstrated to be safe, effective, sustainable and affordable should be deployed alongside conventional mitigation methods as soon as they can be made available;

- SRM methods should not be applied unless there is a need to rapidly limit or reduce global average temperatures. Because of the uncertainties over side-effects and sustainability they should only be applied for a limited time period, and if accompanied by aggressive programmes of conventional mitigation and/or Carbon Dioxide Removal so that their use may be discontinued in due course.

What about **CE-Research**?

Arguments in favour of CE-research:

- Preparedness (society should be prepared in case of severe problems with climate change)
- Avoid adverse side effects
- Chose best approach (in case CE really needs to be applied)

Arguments against CE-research:

- Once the technologie exists it will be applied
- Resources are diverted from mitigation and adaptation research
- False feeling of security (if there is a problem we will apply CE)

The “Oxford Principles” for CE-**Research**

Set of principles for the conduct of geoengineering research drafted by a UK-based team of scholars and presented to the House of Commons Science and Technology Select Committee’s report on “The Regulation of Geoengineering”.

They state:

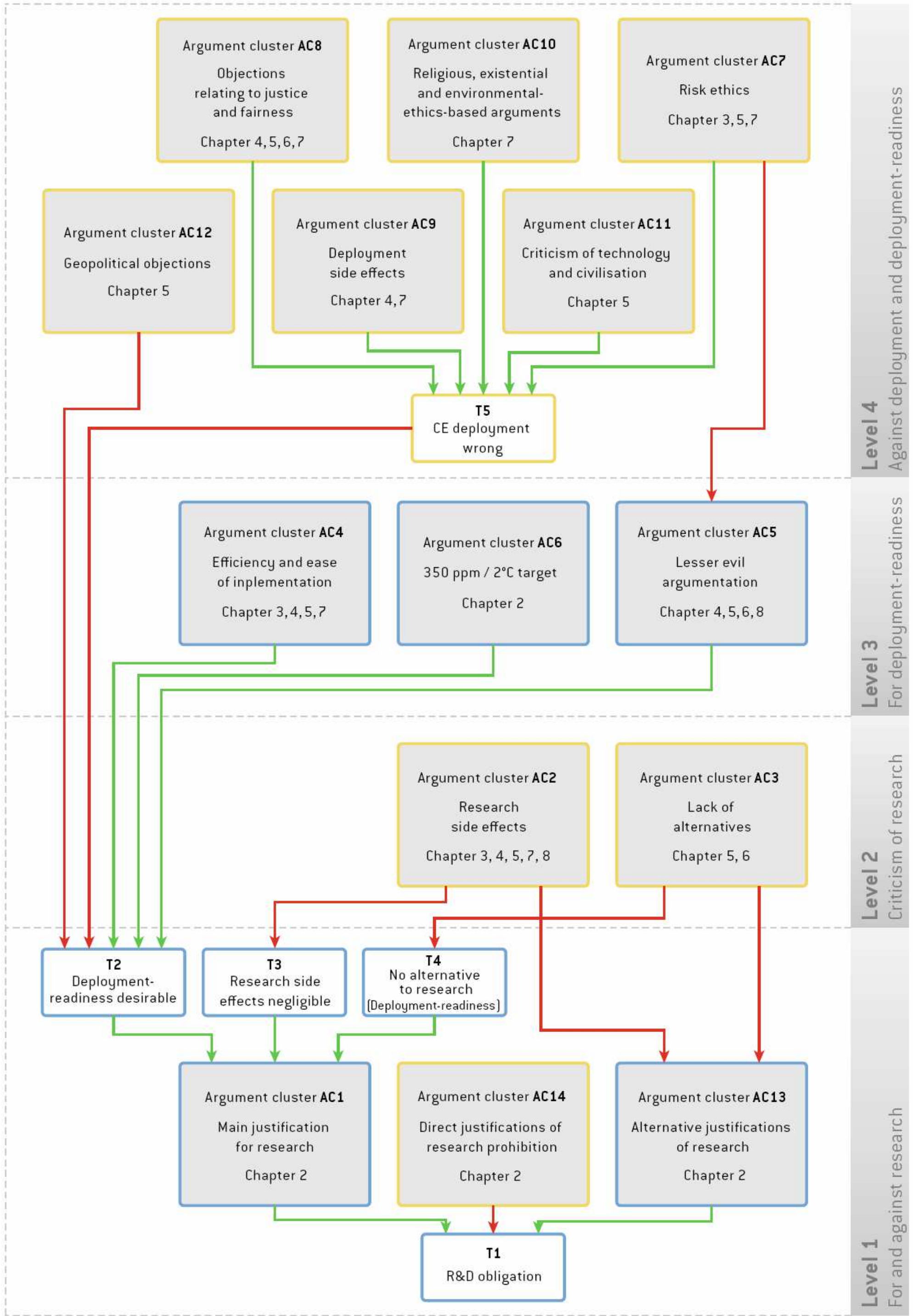
1. Geoengineering to be regulated as a public good.
2. Public participation in geoengineering decision-making.
3. Disclosure of geoengineering research and open publication of results.
4. Independent assessment of impacts.
5. Governance before deployment.

Debate on CE

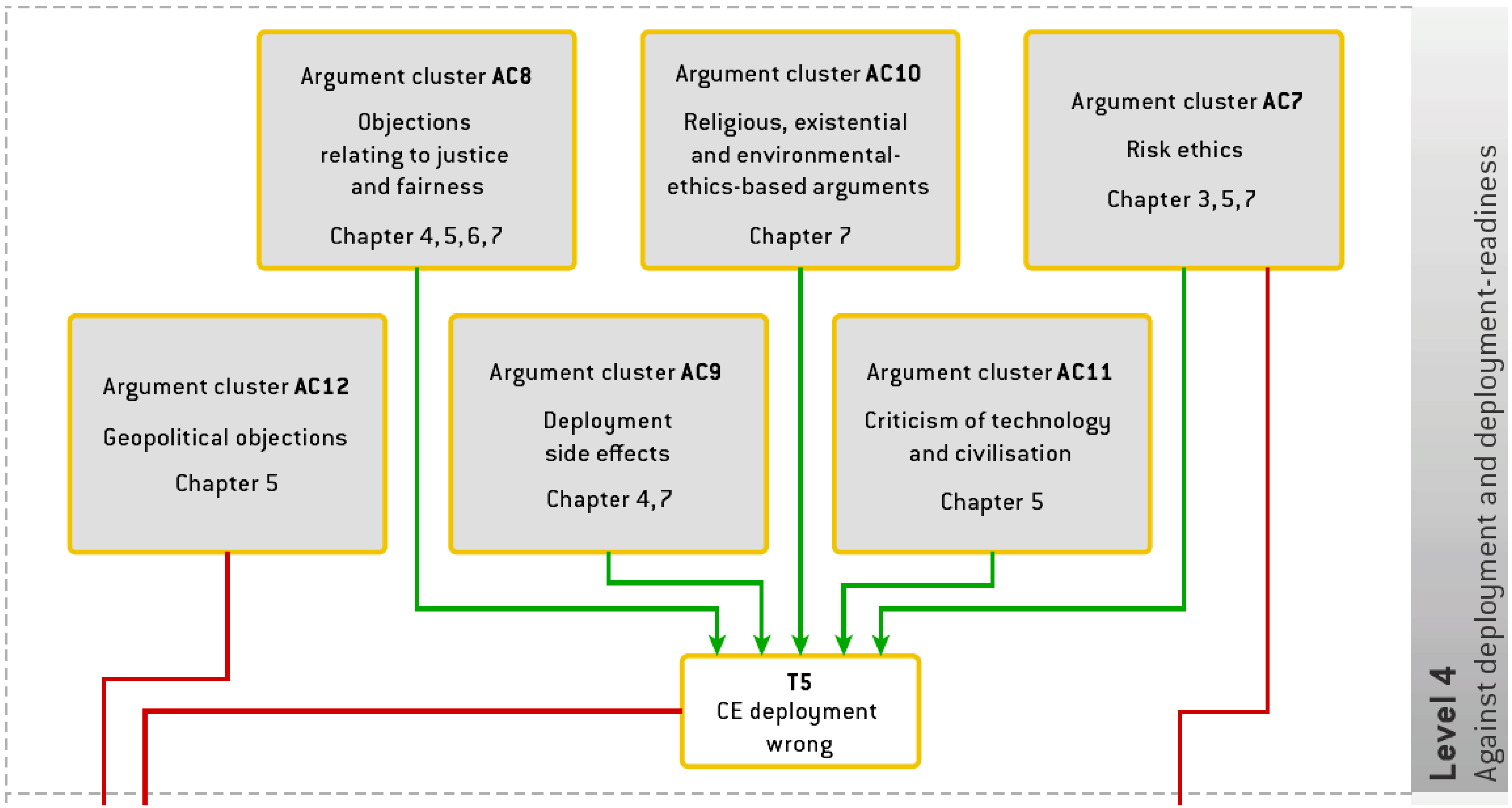
The „argument map“

Betz 2010

(also: Rickels et al. 2011, BMBF scoping study)

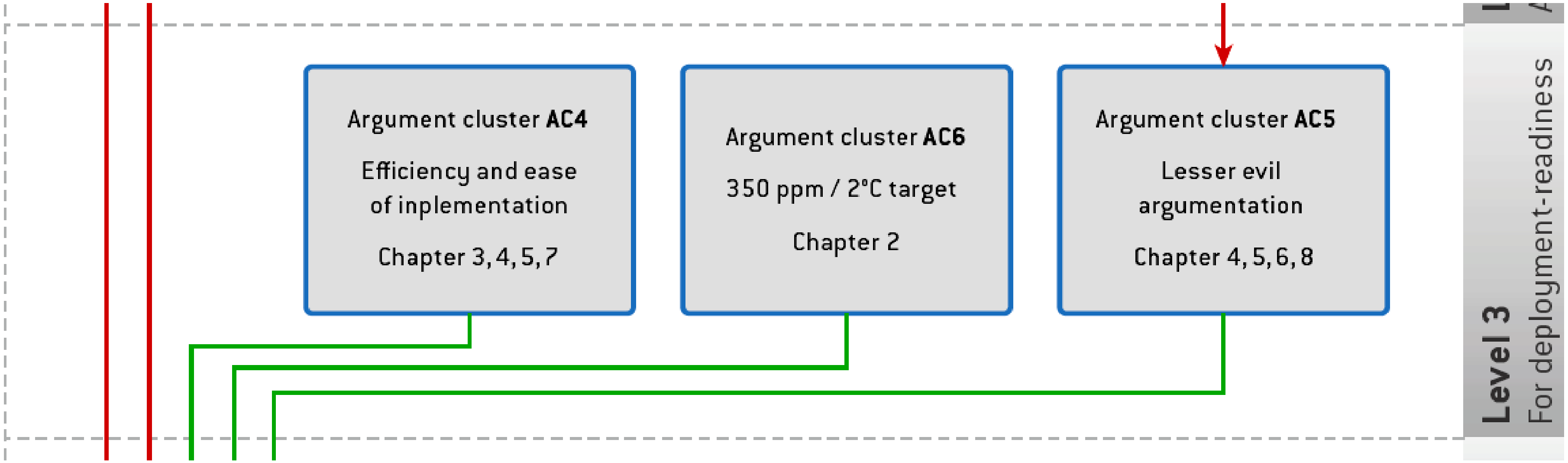


Against Deployment



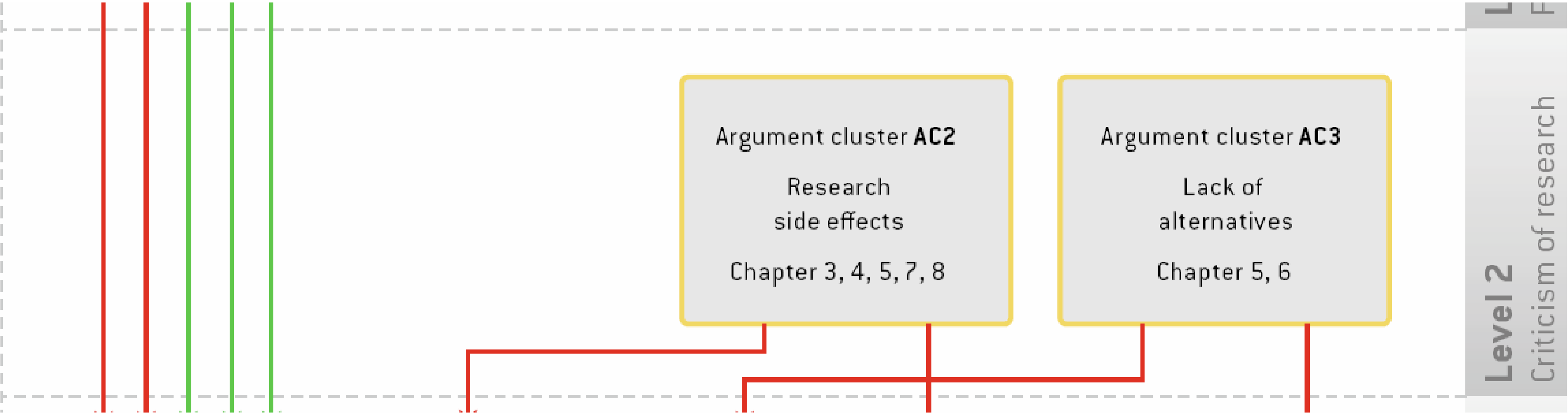
Rickels et al. 2011, BMBF scoping study

For Deployment



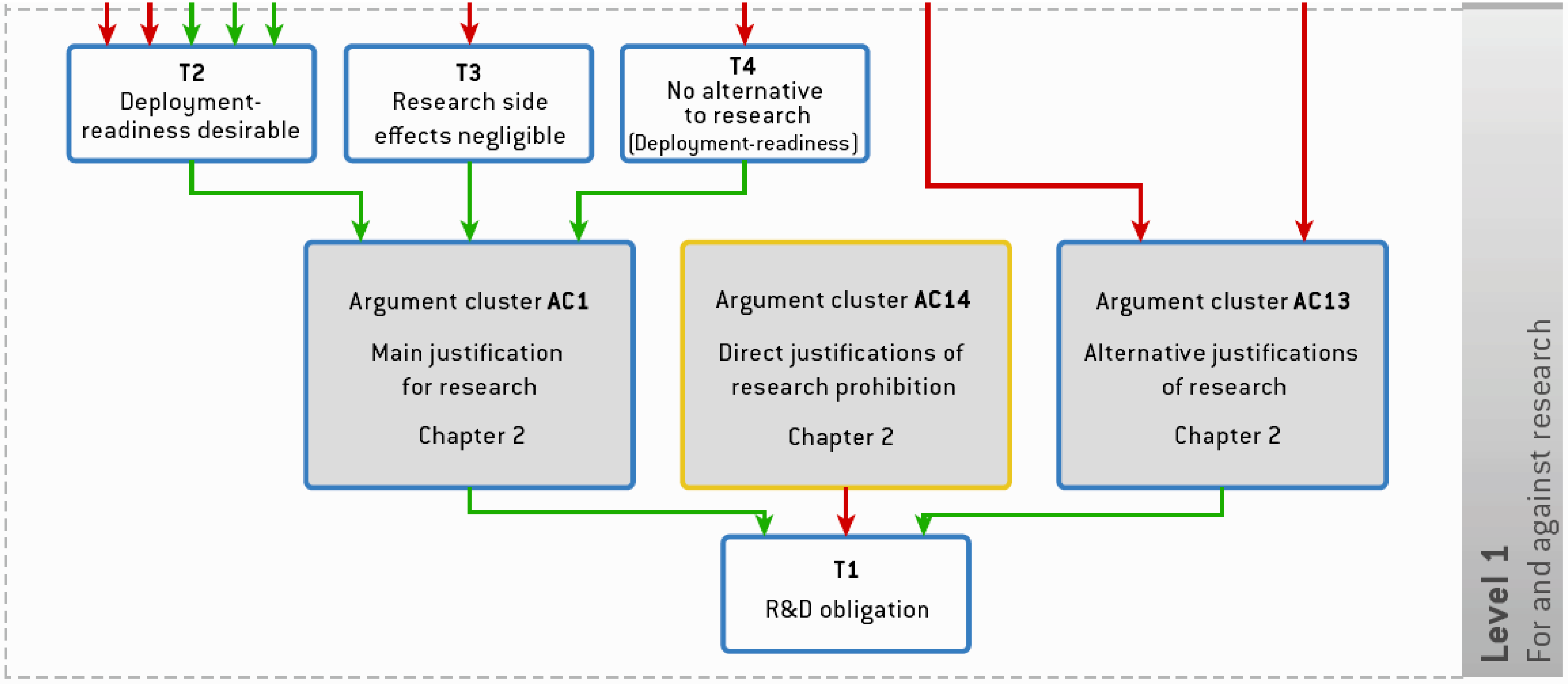
Rickels et al. 2011, BMBF scoping study

Criticism of Research



Rickels et al. 2011, BMBF scoping study

About Research

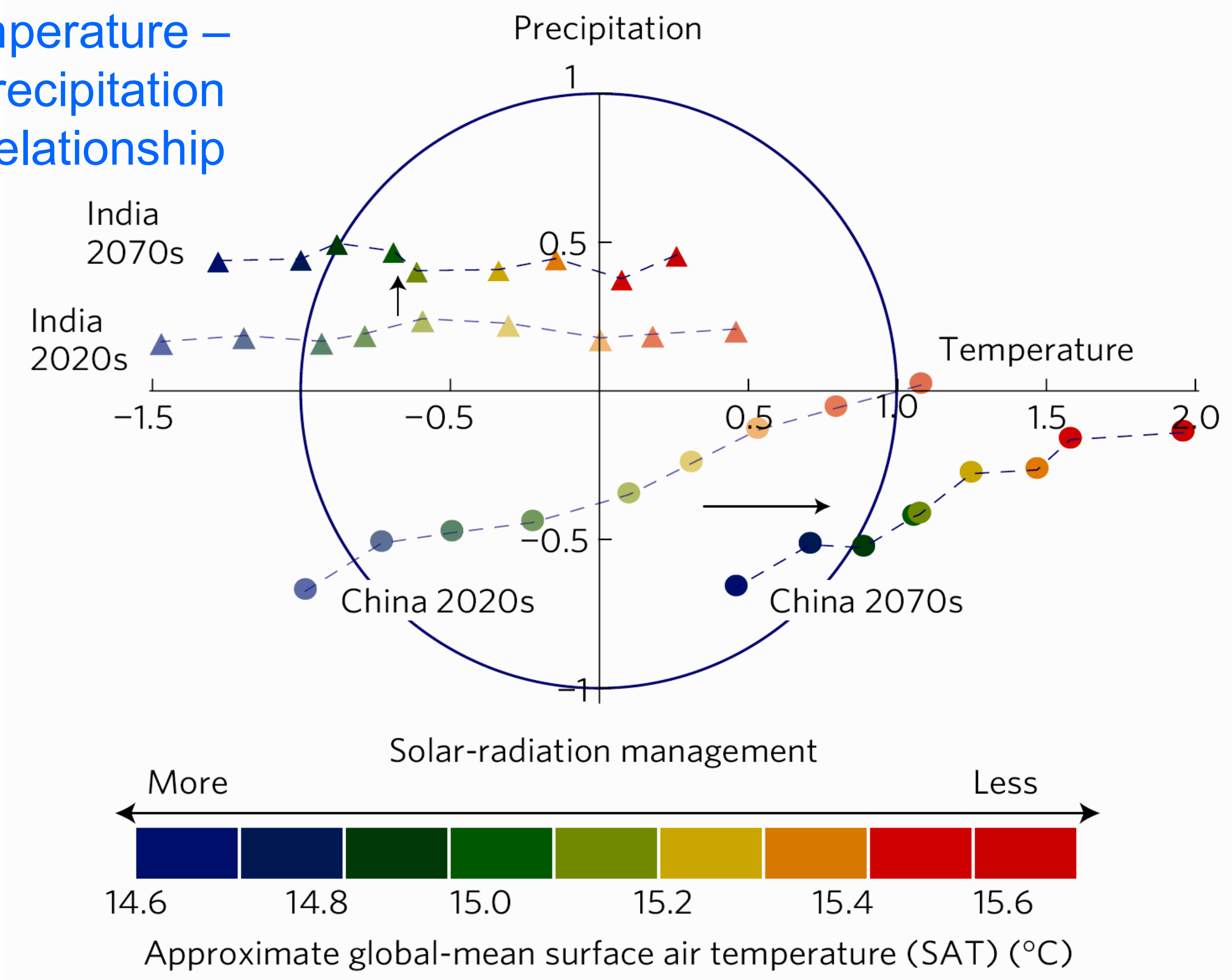


Rickels et al. 2011, BMBF scoping study

The Problem of Politics

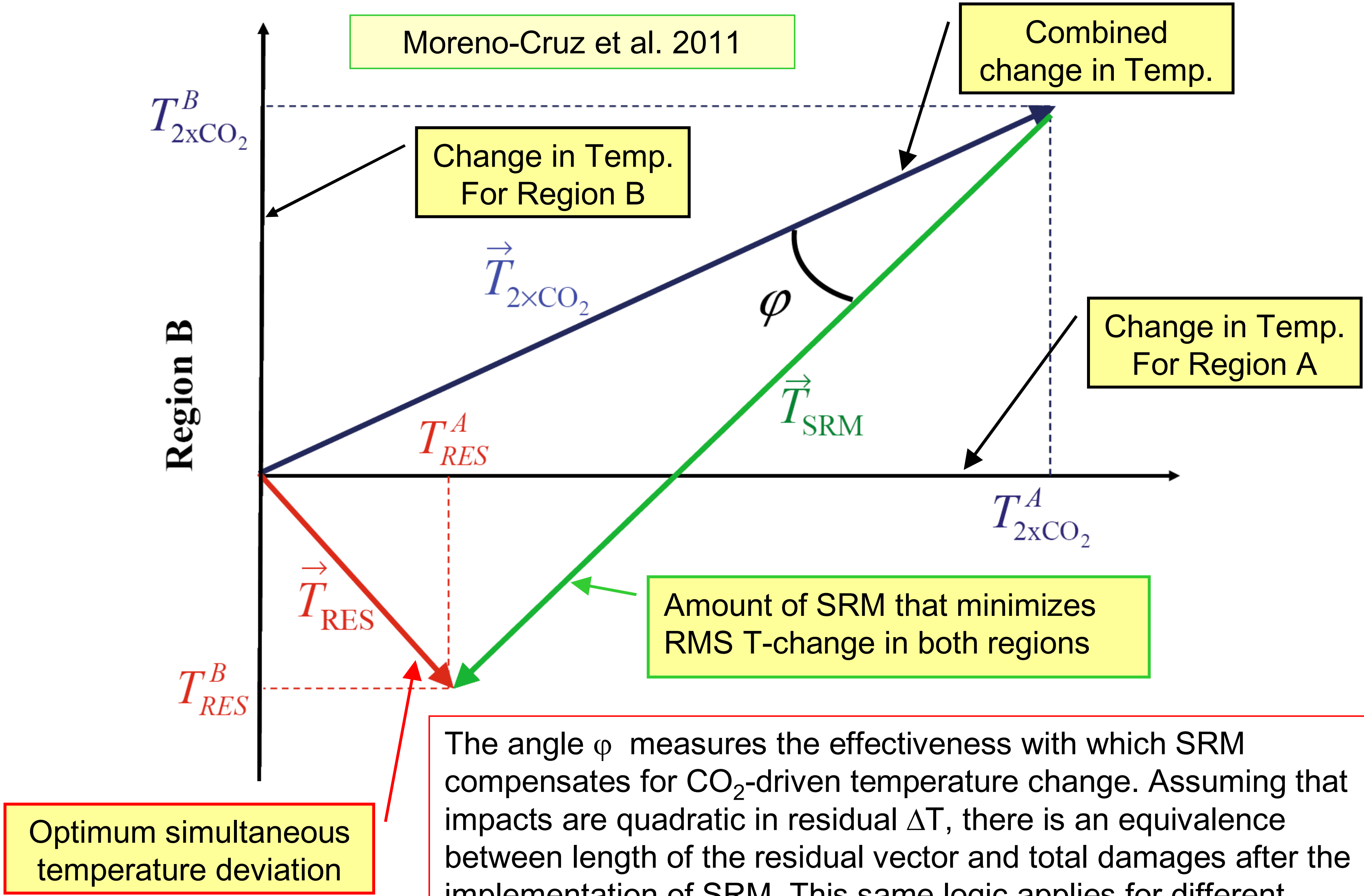
Temperature – Precipitation Relationship

Ricke et al. 2010



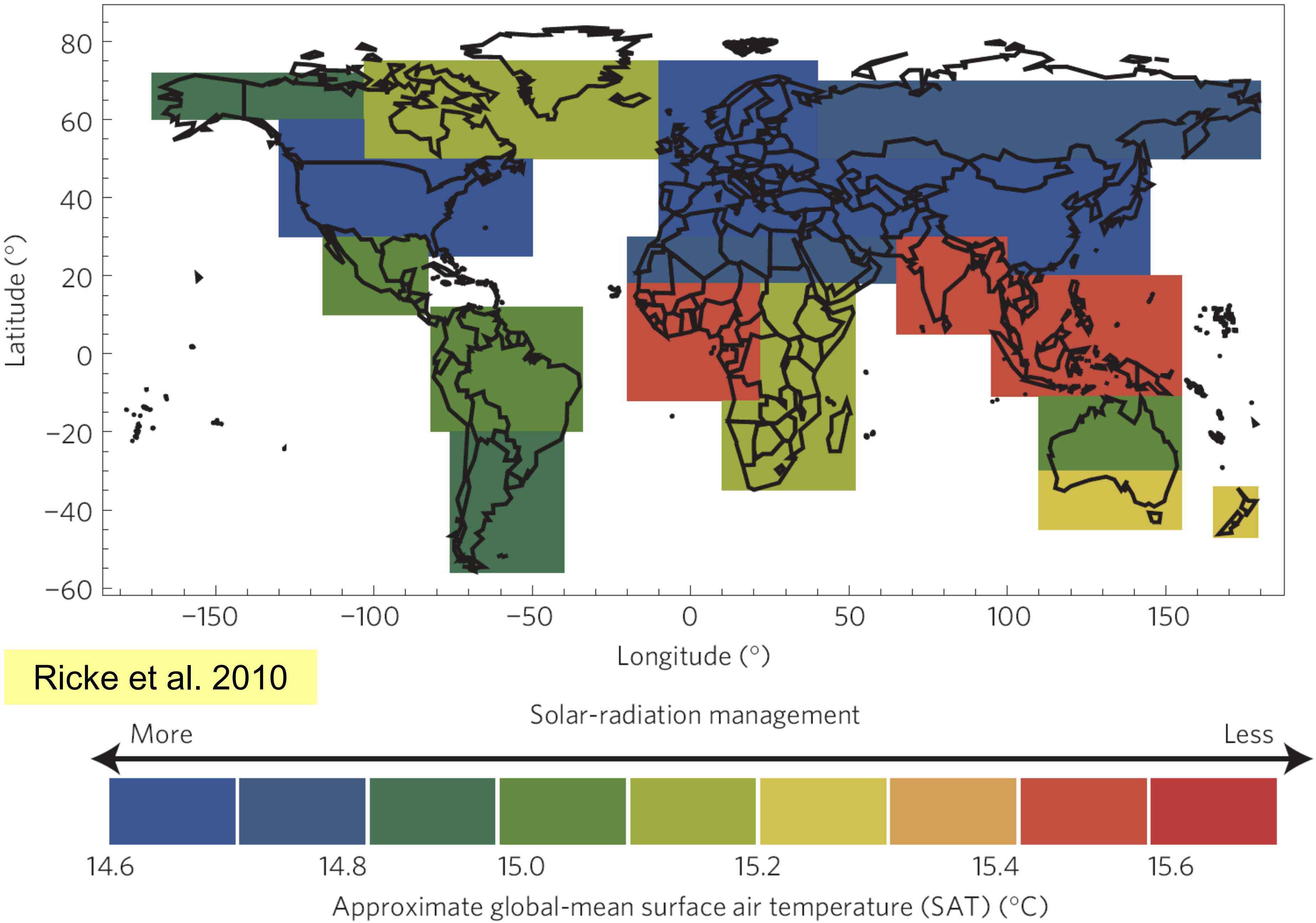
Modelled response to different levels of average global solar-radiation management (SRM) over time in India and China. Interannual-variability-normalized regional temperature and precipitation summer (June, July and August) anomalies (averages for the 2020s minus the 1990s and 2070s minus the 1990s) in units of baseline standard deviations for the region including India (triangles) and the region including eastern China (circles). SRM-modified climates for these two regions migrate away from the baseline in disparate fashions.

Residual Climate Response Model



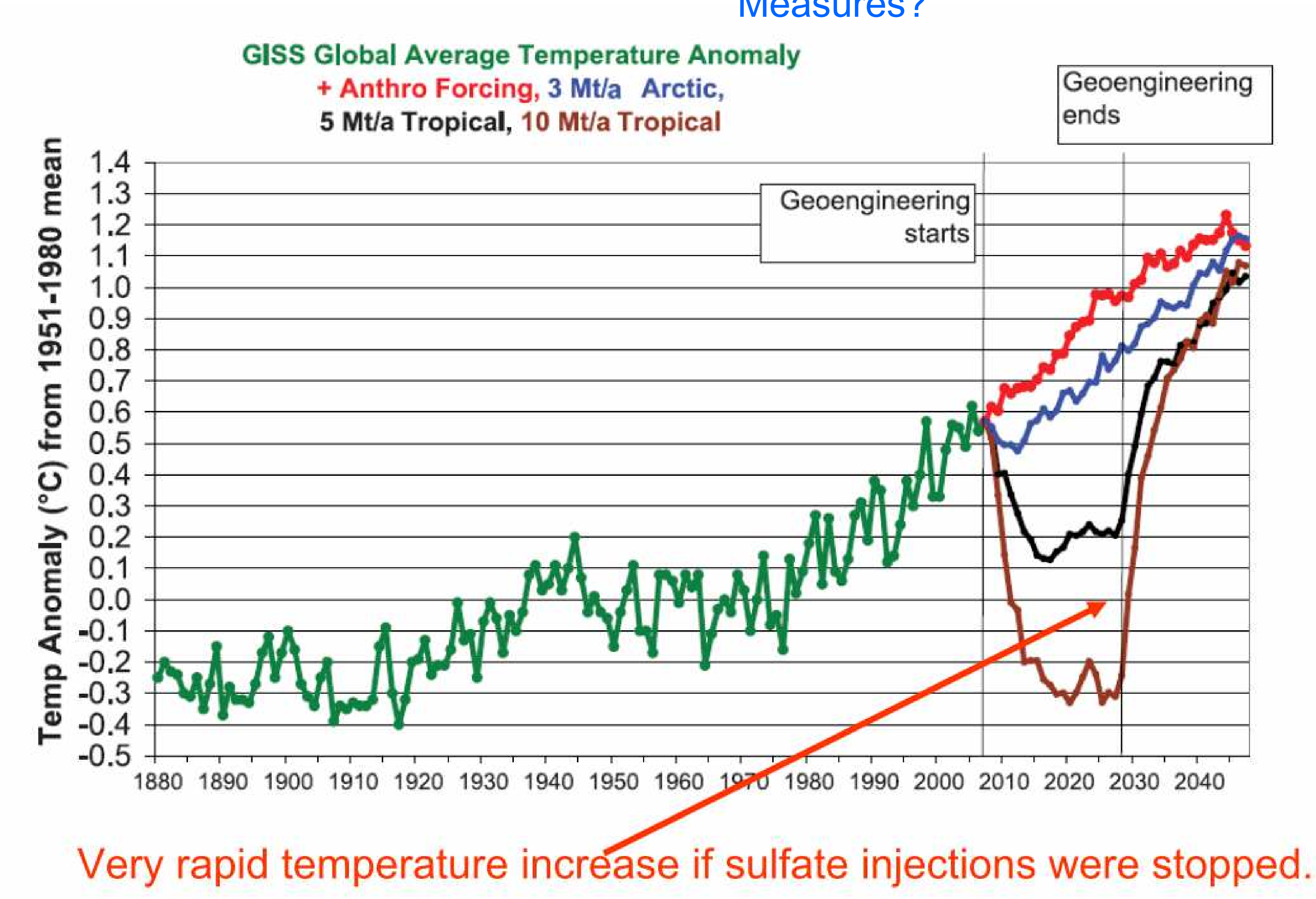
The angle φ measures the effectiveness with which SRM compensates for CO_2-driven temperature change. Assuming that impacts are quadratic in residual ΔT, there is an equivalence between length of the residual vector and total damages after the implementation of SRM. This same logic applies for different climate variable (e.g. precipitation) and more than two regions

„Optimal“ CE 2070‘s = Level of Ce that brings combined T and precipitation closest to 1990 values



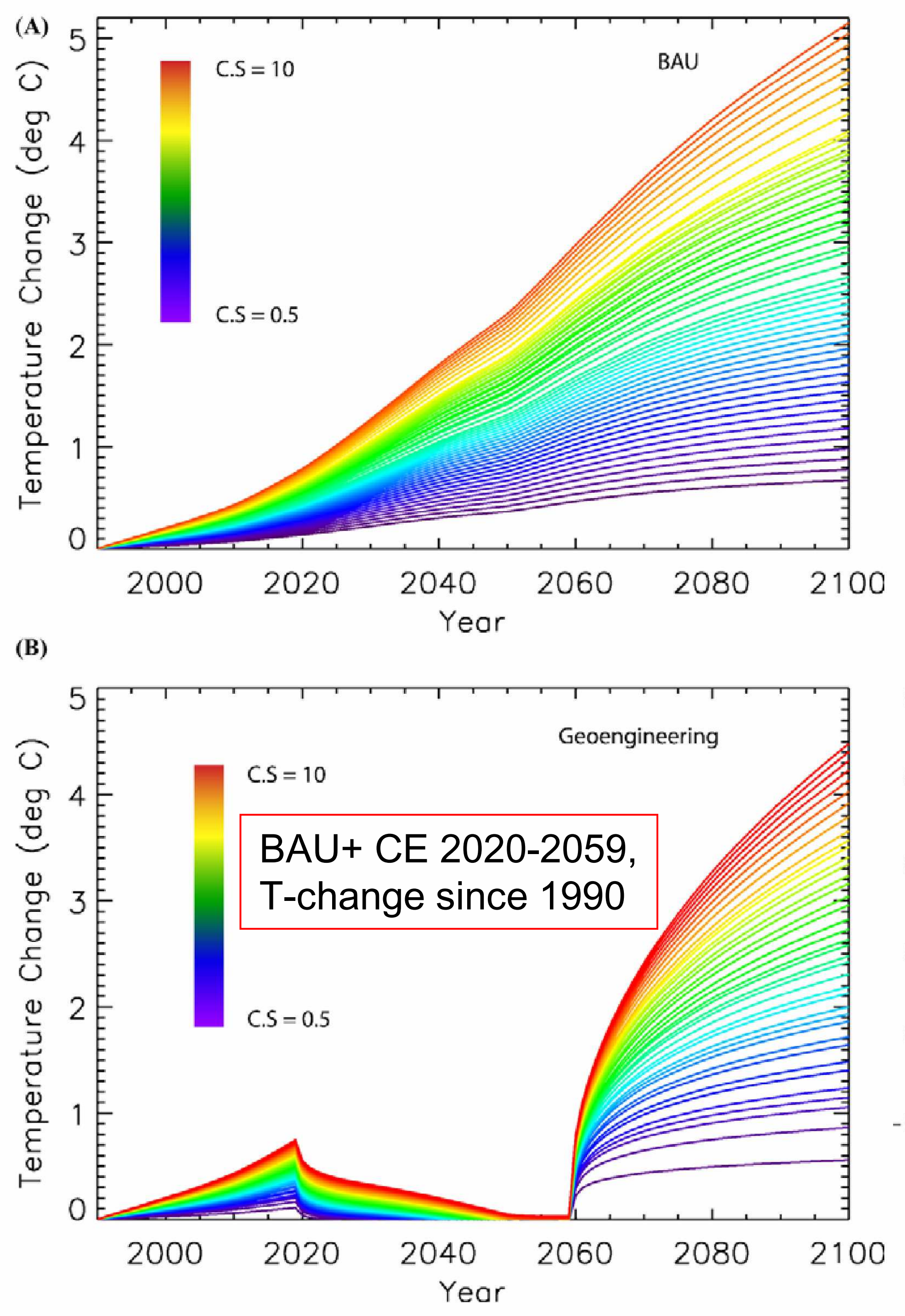
Ricke et al. 2010

What Happens if we stop Climate Engineering Measures?



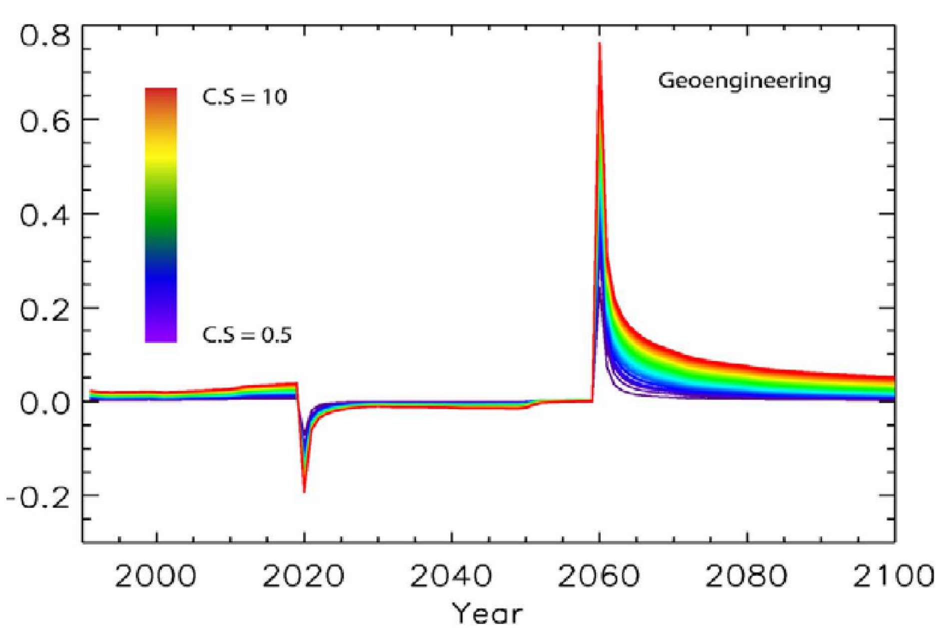
Robock et al. JGR 2008

Terminate d CE



Busness as usual (BAU), T-change since 1990

Ross Matthews 2009



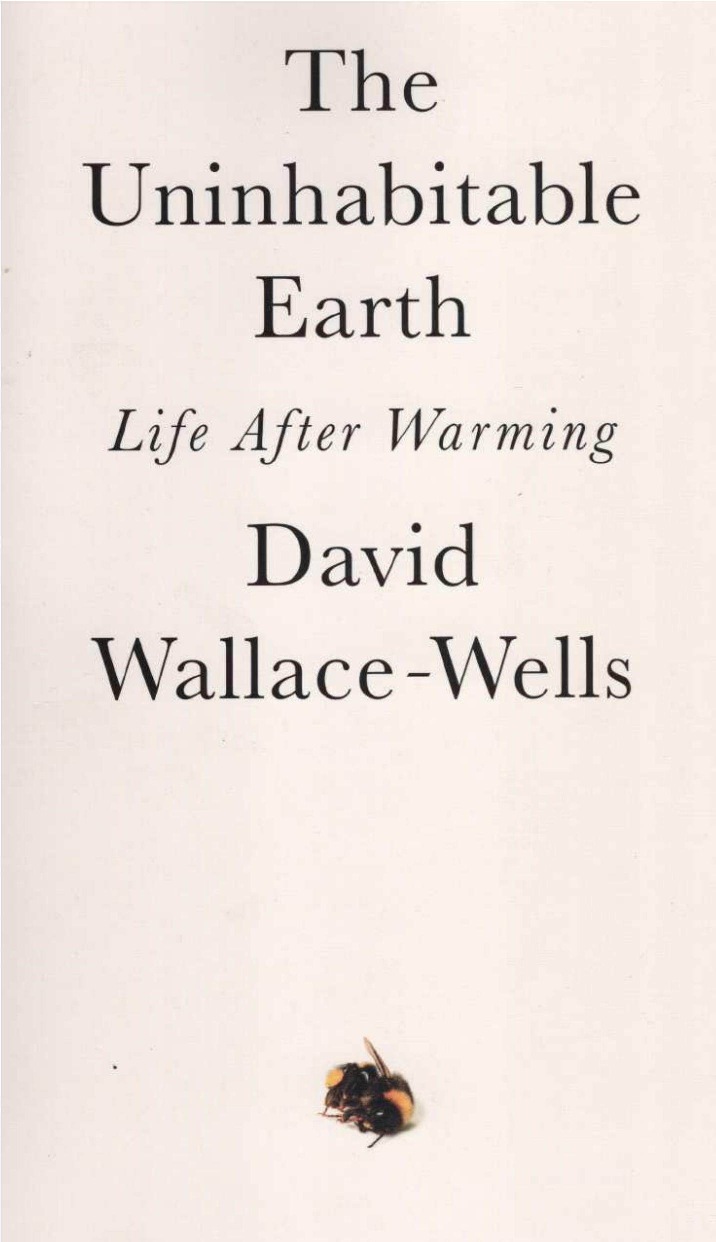
Really Roughly Estimated Cost of CE-measures (10^9 US$ per W/m^2)

Reduction of CO_2 Emission:	200 (for comparison)
Urban albedo reduction:	2000
Desert albedo reduction:	1000
Cloud Whitening:	0.135 (or more)
Stratospheric S-Aerosol:	2-67
Space Shades:	1700 (L1)

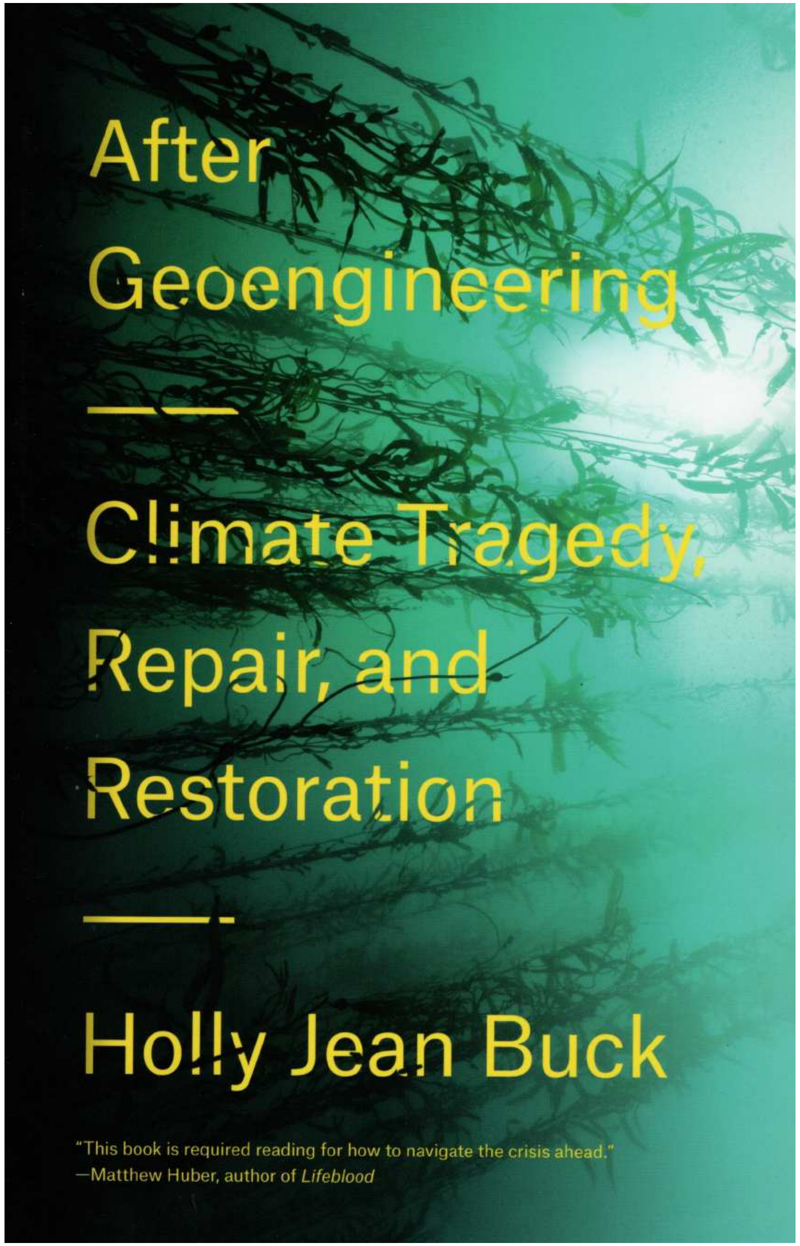
Source: Rickels et al. 2011 (BMBF-Report)

Summary

- Climate modification measures are already being applied to our planet (Emission of greenhouse gases, deforestation, etc.) – although not deliberate.
- The idea to add deliberate Climate Engineering to these measures may appear blasphemic, however there might be emergency situations where CE may be the only solution (e.g. because of time scales).
- CE might not be feasible at all or much more difficult (and expensive) to implement than anticipated.
- There are great dangers associated with CE:
  - Moral dangers – less incentive for mitigation („Climate Sceptics“: „Climate change is not a problem and CE is the solution“)
  - Side effects and unwanted effects
  - Political disturbances
- However, research can answer some of these questions and reduce some of the uncertainties.



TIM DUGGAN BOOKS, 2019



VERSO London, New York, 2019