Responding to Climate Change
Is Climate Engineering an Option?

Tom Ackerman

Professor, Department of Atmospheric Sciences

Director, Joint Institute for the Study of the Atmosphere and Ocean

University of Washington

W COLLEGE of the ENVIRONMENT
UNIVERSITY of WASHINGTON

JISAO

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- Rob Wood (*Department of Atmospheric Sciences, UW*)
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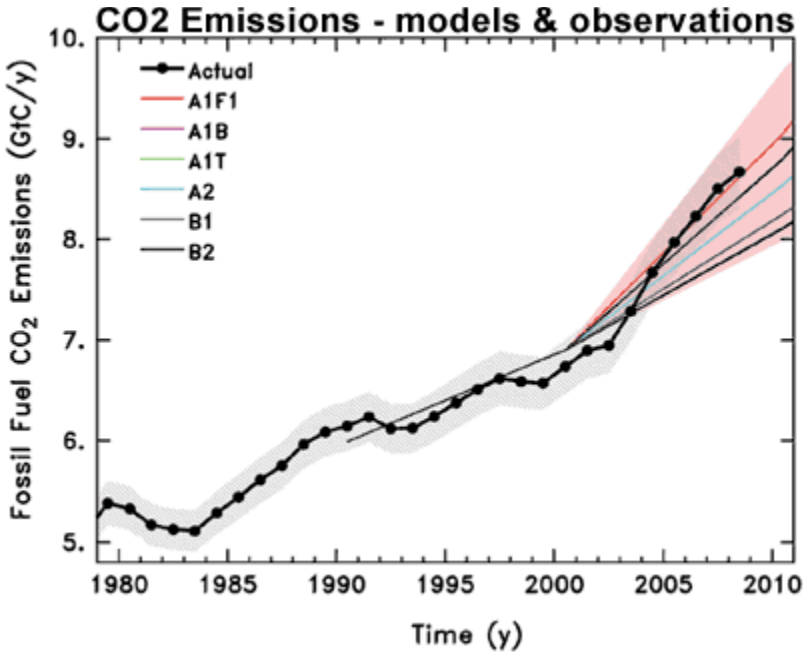
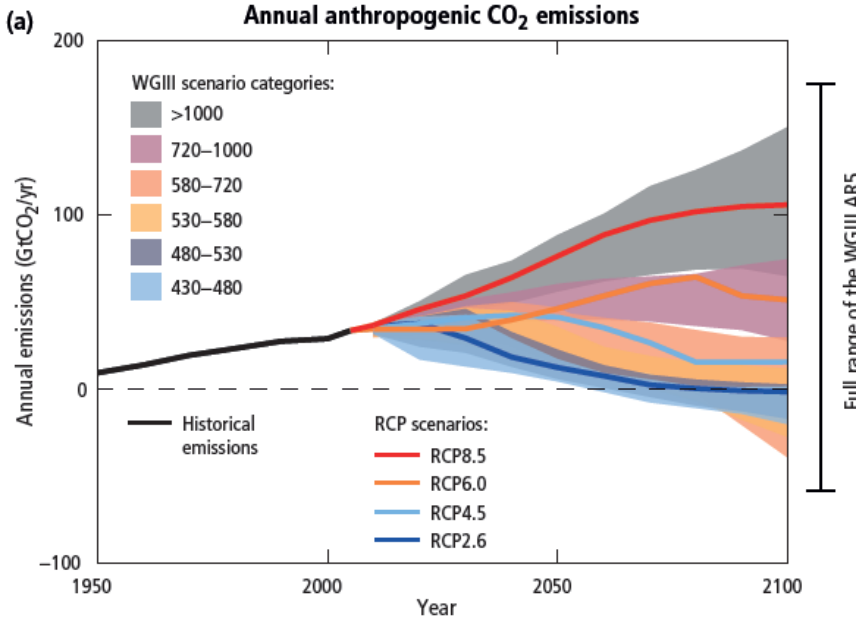
- Stephen Gardiner (*Department of Philosophy, UW*)

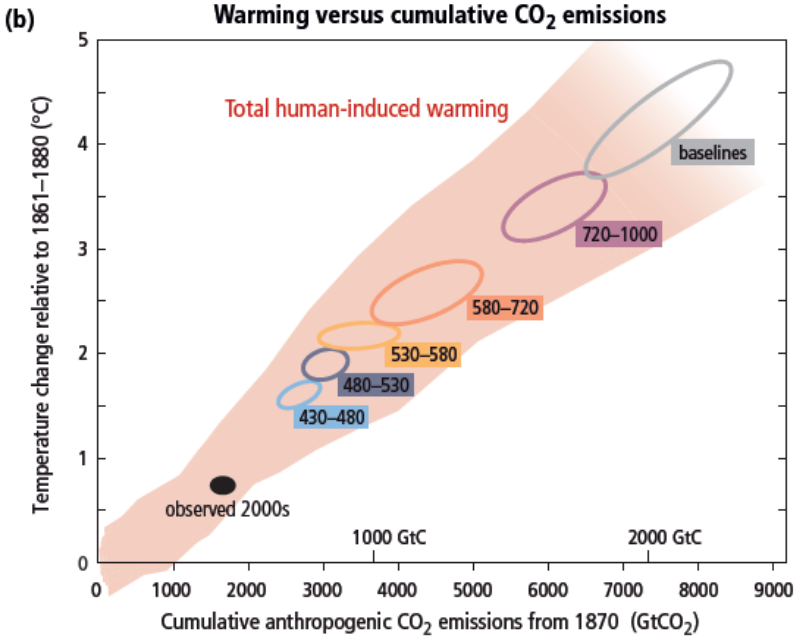
- Armand Neukermans (*Consulting engineer*)

The Problem

- CO2 concentrations are increasing at a rate that exceeds "business as usual"
- Temperature change will pass the "2 degree" danger point by mid-century







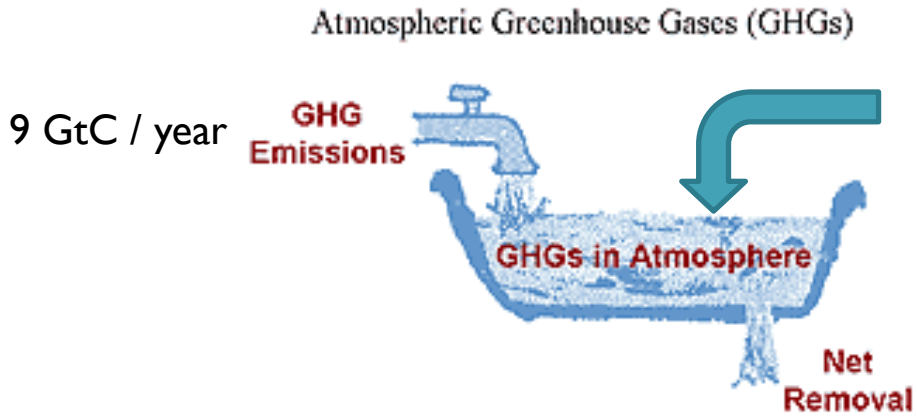
What is the solution?

- Reduce greenhouse gas concentrations

However,

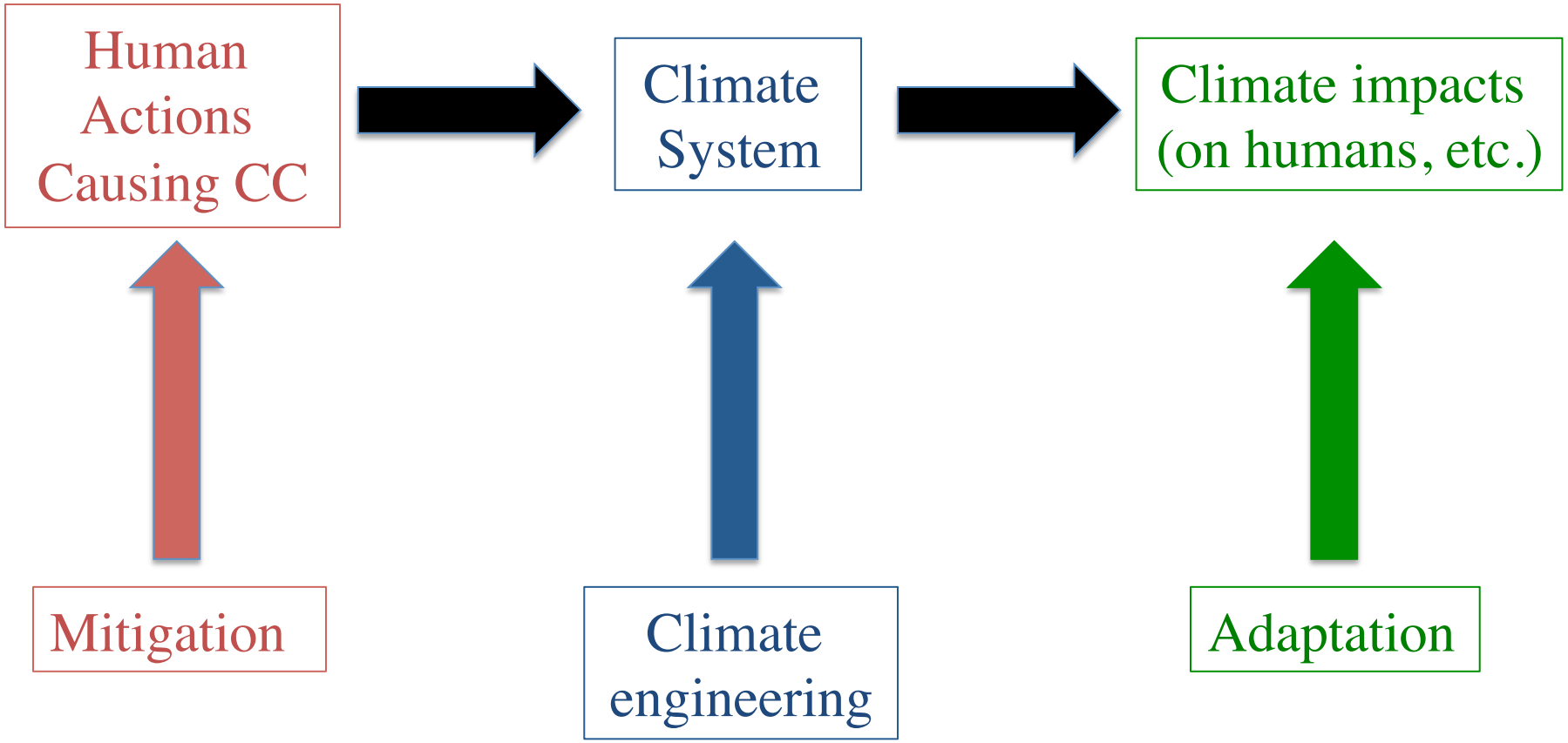
We are not doing much of anything to reduce emissions!

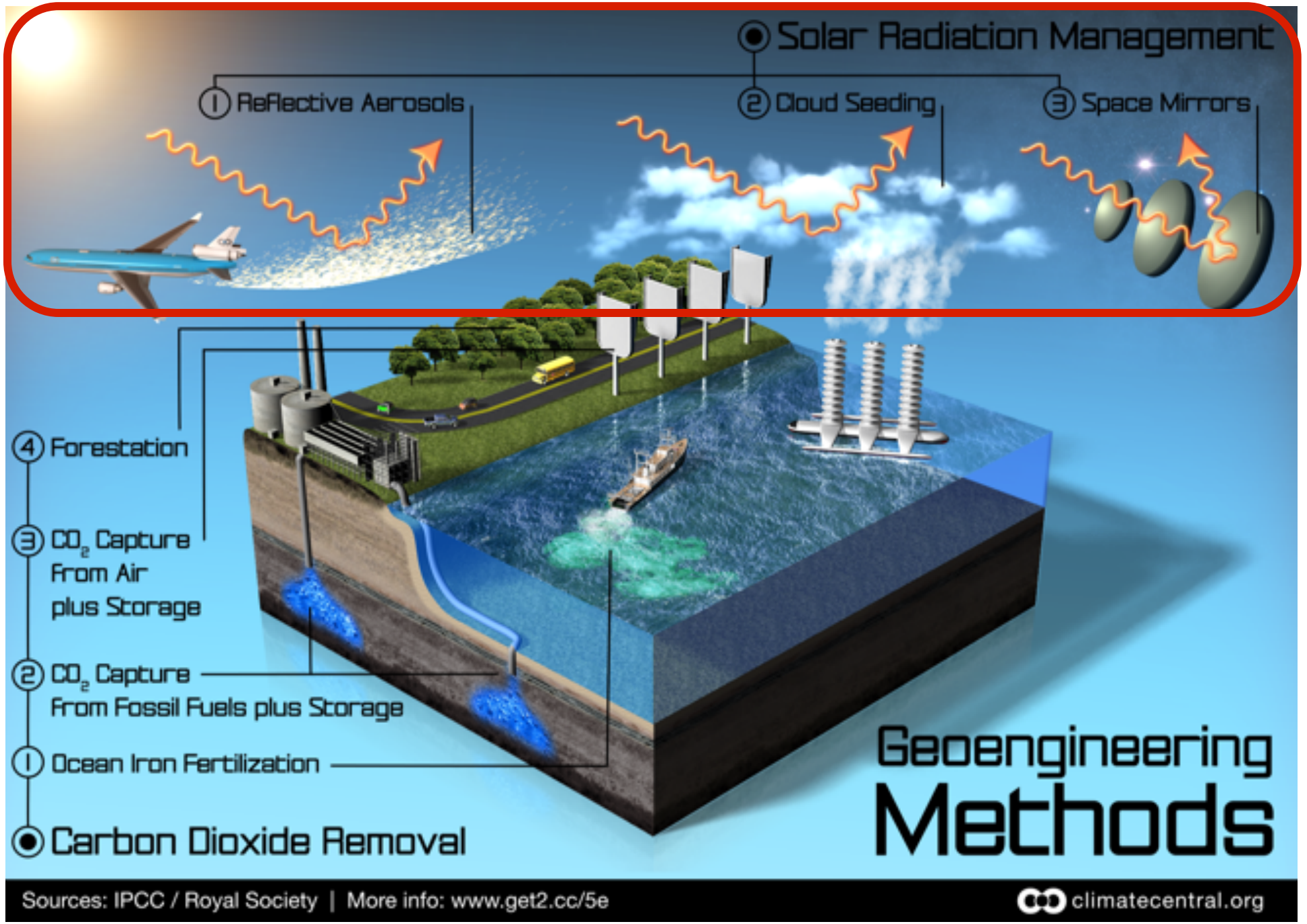
What happens if we decide climate is getting too warm and we want to slow that warming?



Atmospheric conc.
~390 ppm
Increase of ~2 ppm/yr

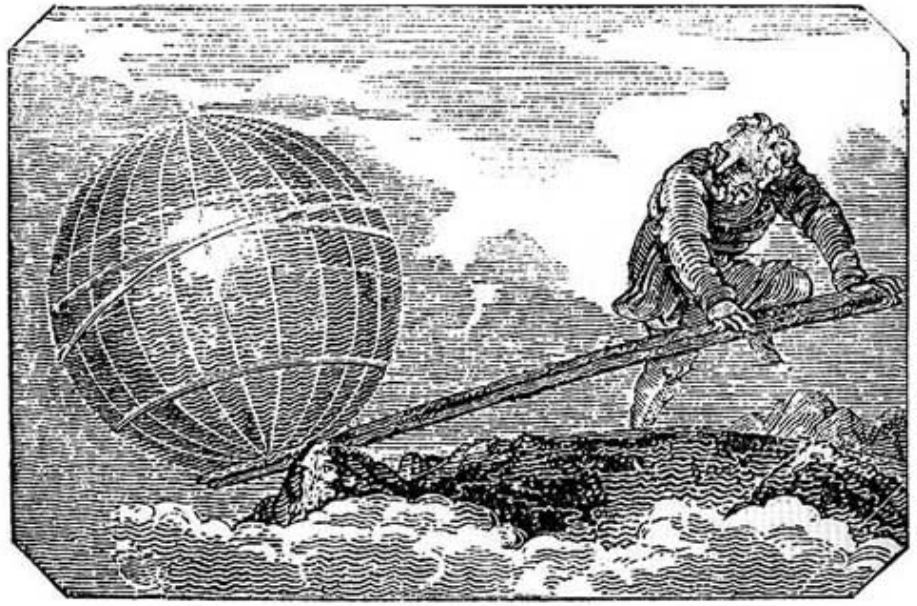
Human contribution to global carbon cycle
(1 Gt = 1 billion metric tons)


Human Actions Causing CC
Climate System
Climate impacts (on humans, etc.)
Mitigation
Climate engineering
Adaptation


Solar Radiation Management
1 Reflective Aerosols
2 Cloud Seeding
3 Space Mirrors
4 Forestation
3 CO_2 Capture From Air plus Storage
2 CO_2 Capture From Fossil Fuels plus Storage
1 Ocean Iron Fertilization
Carbon Dioxide Removal
Geoengineering Methods
Sources: IPCC / Royal Society | More info: www.get2.cc/5e
climatecentral.org

Moving the earth …

- Move the earth to an orbit slightly further away from the sun …
- Estimate: move the earth about 220,000 km further "out" to compensate for doubled CO2
- Roughly 2000 km per year should do it!
- About 1/3 of an earth radius per year!

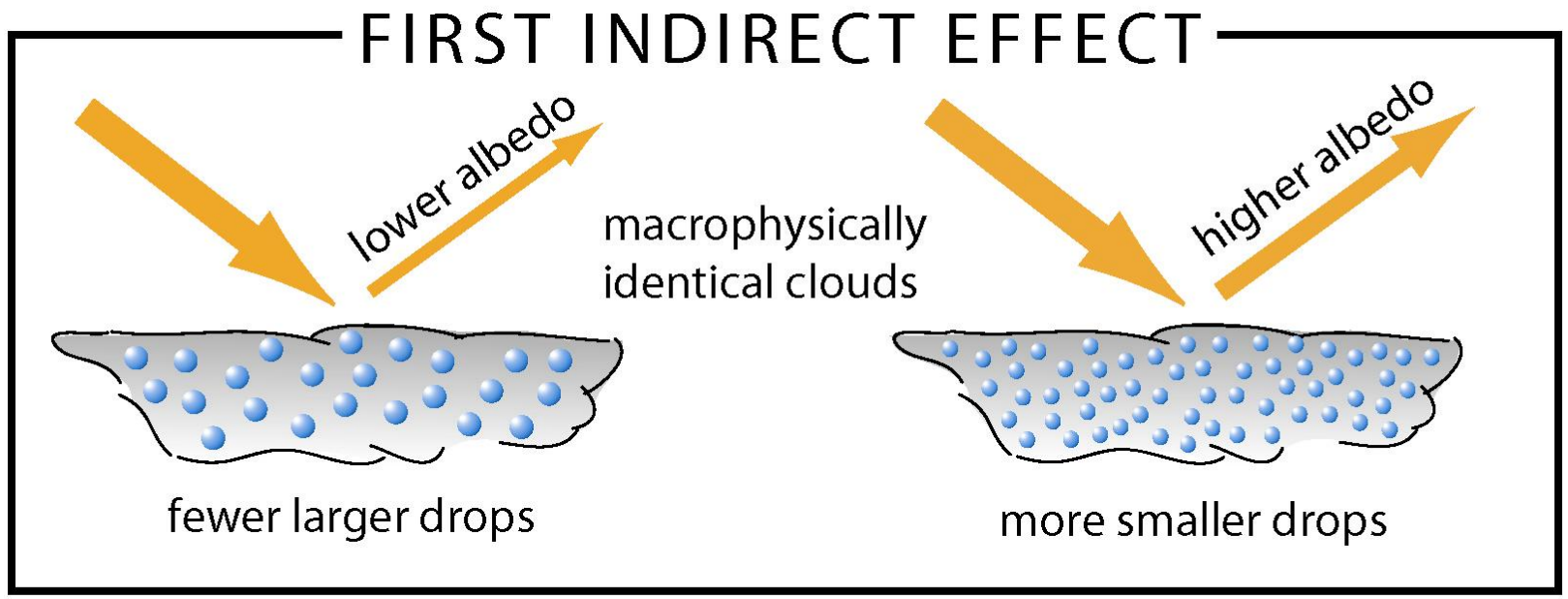


Ship tracks in low clouds over the Pacific Ocean

Marine Cloud Brightening

Cloud Brightening (the simple story)

- **Twomey effect**: for a given condensate amount, more particles lead to more numerous, but smaller cloud droplets (observed in ship-tracks)
- Total droplet surface to volume area increases ⇒ clouds reflect more sunlight
- First suggested as a possible way to mitigate anthropogenic global warming by Latham (1990, Nature); also Slingo (1990)



Latham et al.

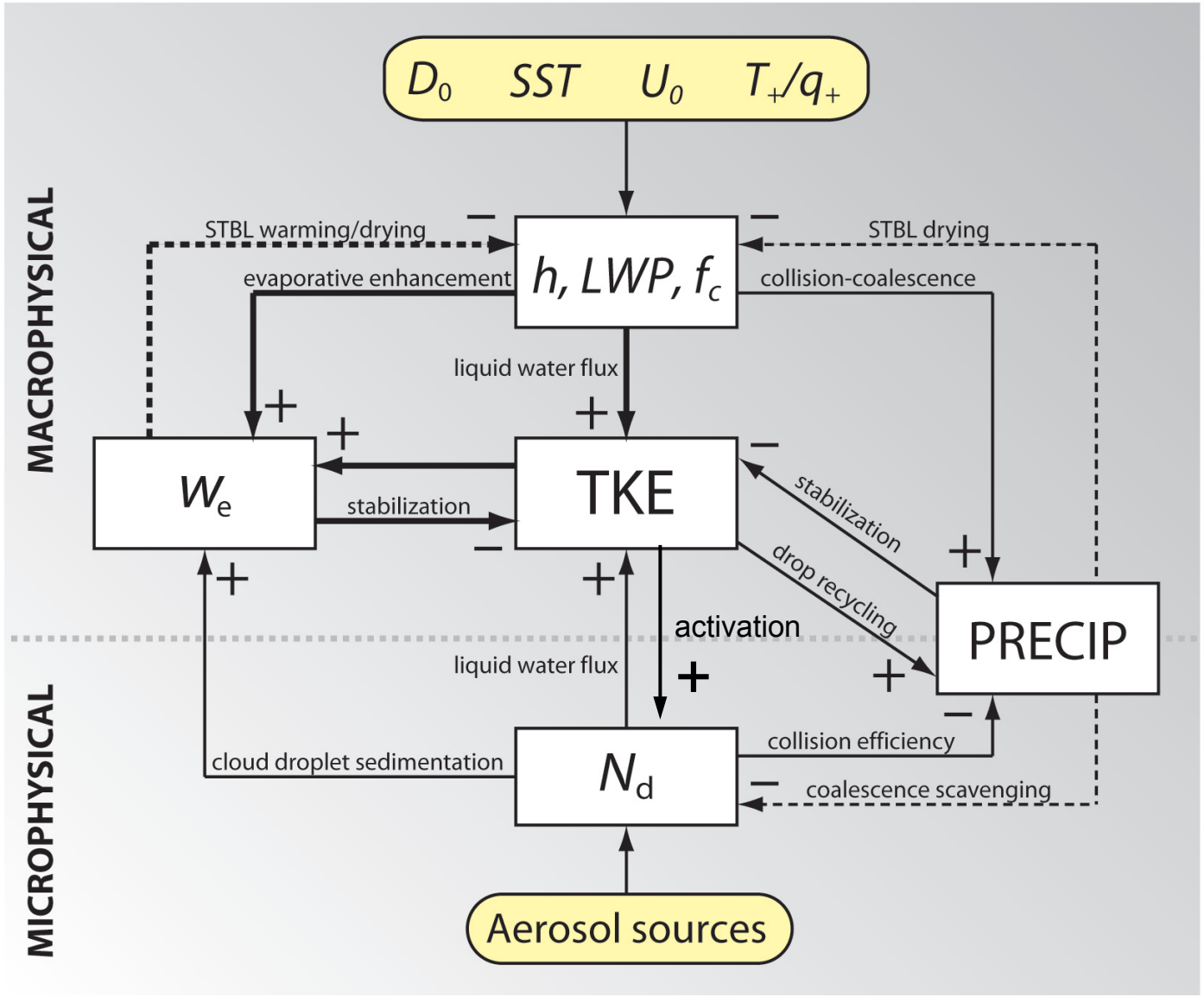
Twomey (1974, 1977)

Why don't we know the magnitude of the cloud-mediated aerosol effect on climate?

Mesoscale circulation:
1 – 1000 km

Boundary layer:
10 – 1000 m

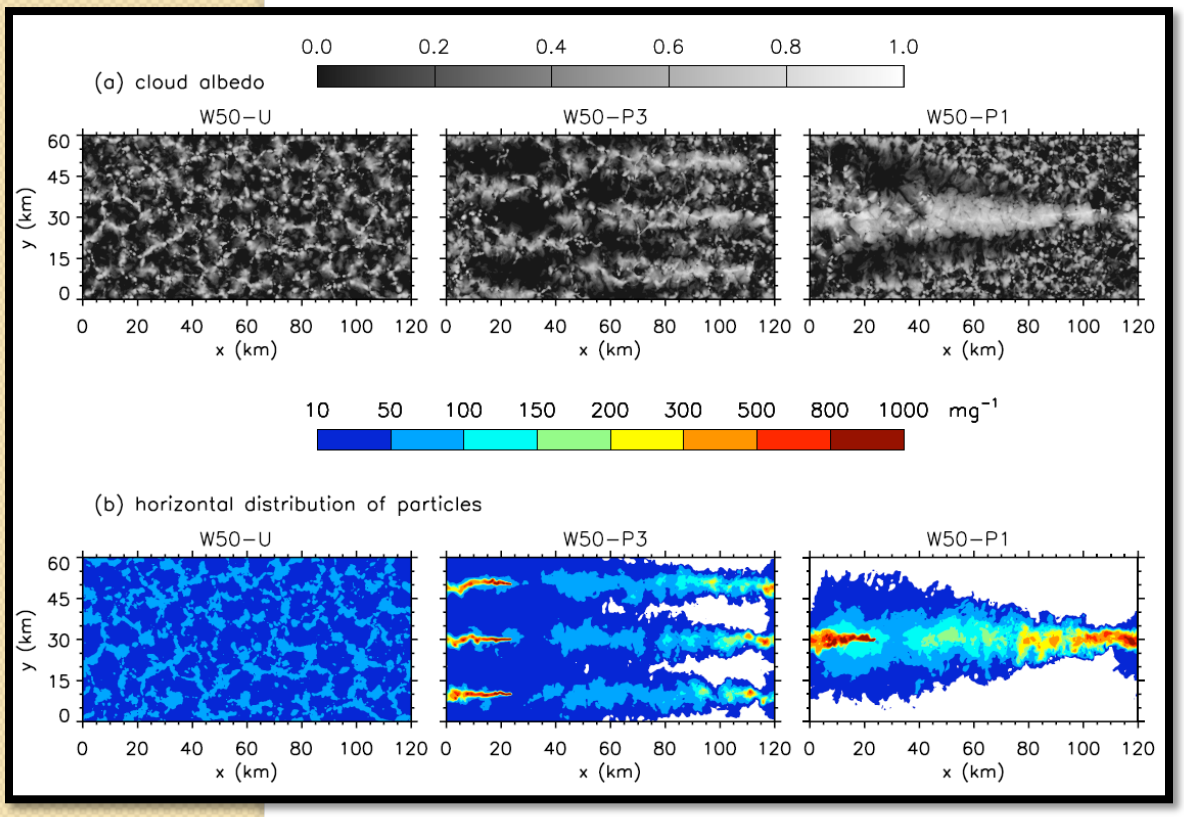
Droplets and aerosol:
Micron scale (10^{-6} m)



Courtesy of Rob Wood

Some of the complications

- MCB depends on
  - Aerosol number, composition, and size
  - State of ambient environment (SST, wind, subsidence, etc.)
  - Feedback from modified cloud to boundary layer dynamics



- Aerosol may enhance brightening along plume but suppress it in adjacent areas (Wang et al. 2011)
- Teleconnections to regions other than that seeded are not clearly understood (Parkes et al. 2012; Jones et al., 2011)

What do scientists do when confronted by a poorly understood problem?

- Do an experiment: Provide critical information for understanding aerosol indirect effects by studying effects of a known aerosol injection
- Test key physical processes in MCB
- Test predictive models of aerosol injection and cloud response, including radiative effects

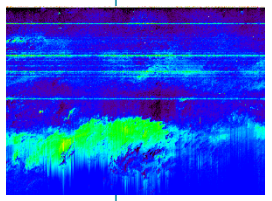
This is a paradigm shift in atmospheric sciences

- Using the atmosphere as a laboratory
- Seeking to understand a "control" technology
- Not completely unprecedented (cloud seeding)

Key Processes for Experimental Investigation

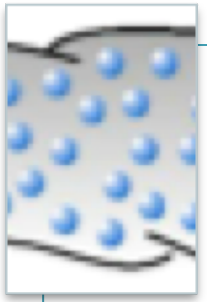
Generating controlled perturbation →

Creation and injection of particles into the marine boundary layer

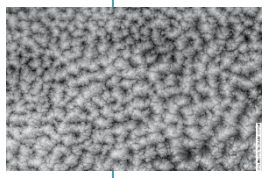


Dispersion of particles within the marine boundary layer

Cloud response →

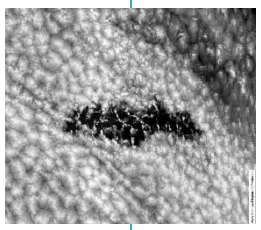


Microphysical responses of clouds upon ingestion of aerosols



Dynamical/macro-physical responses of clouds (turbulence, entrainment, cloud thickening/thinning)

Cloud Reflectivity and Feedbacks →



Overall effect of the microphysical and dynamical responses on cloud radiative properties

Marine Cloud Brightening Experiment

Comments

- Stage 0 – nearing completion; have some funding for modeling
- Stage 1 – have proposal but no funding
- Stage 2 – reasonably straight-forward extension of Stage 1
- Stage 3 – "way out there"

Phases of Stage 1 (proposed)

PHASE 1
- Spray system development, site preparation & detailed planning

PHASE 2
- Test spray system dispersion using scanning lidar

PHASE 3
- Test spray system dispersion & size distribution in coastal environment (includes aircraft and ground-based measurements) (3 months)

PHASE 4
- Test effect of particle injection into the boundary layer on marine stratus clouds in a coastal environment (pending prior phases)

Technical development - sprayer

- Aerosol generation
  - Estimate of 10^{15} to 10^{17} particles per second per sprayer
  - Prefer 5 sprayers, but 3 is minimum acceptable
- Must be energy efficient and produce salt crystals with mean diameter of about 80 nm

Effervescent ECS nozzle in operation

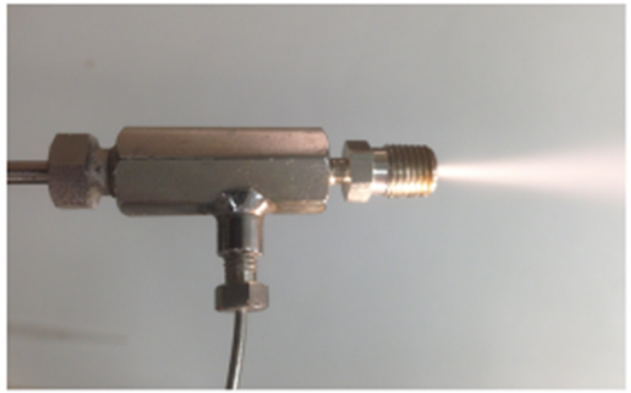
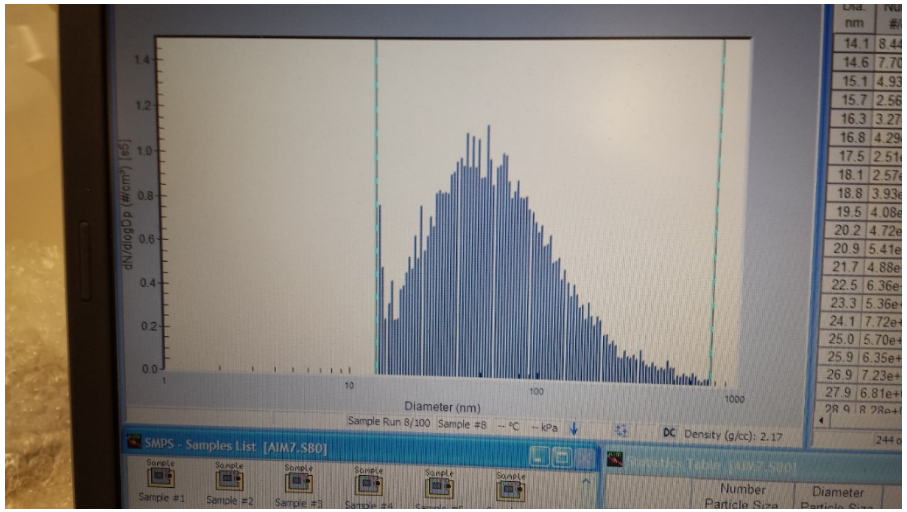
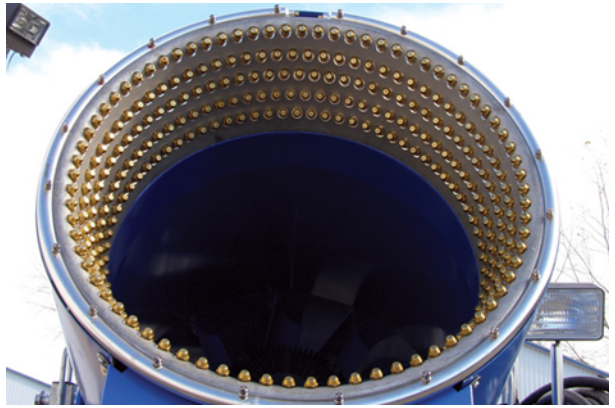


Fig. 2 Effervescent nozzle with gas entering from the left, liquid entering from the lower flow impedance tubing and the sapphire orifice imbedded in the stainless steel nozzle on the right. Note that the divergent spray (2-3 mm diameter is instantly wider than the nozzle (125 um)



Phase 1- Sprayer

- Build outdoor delivery system
- Hundreds of nozzles per sprayer
- Mounted in system with fan to "propel" particles into the atmosphere

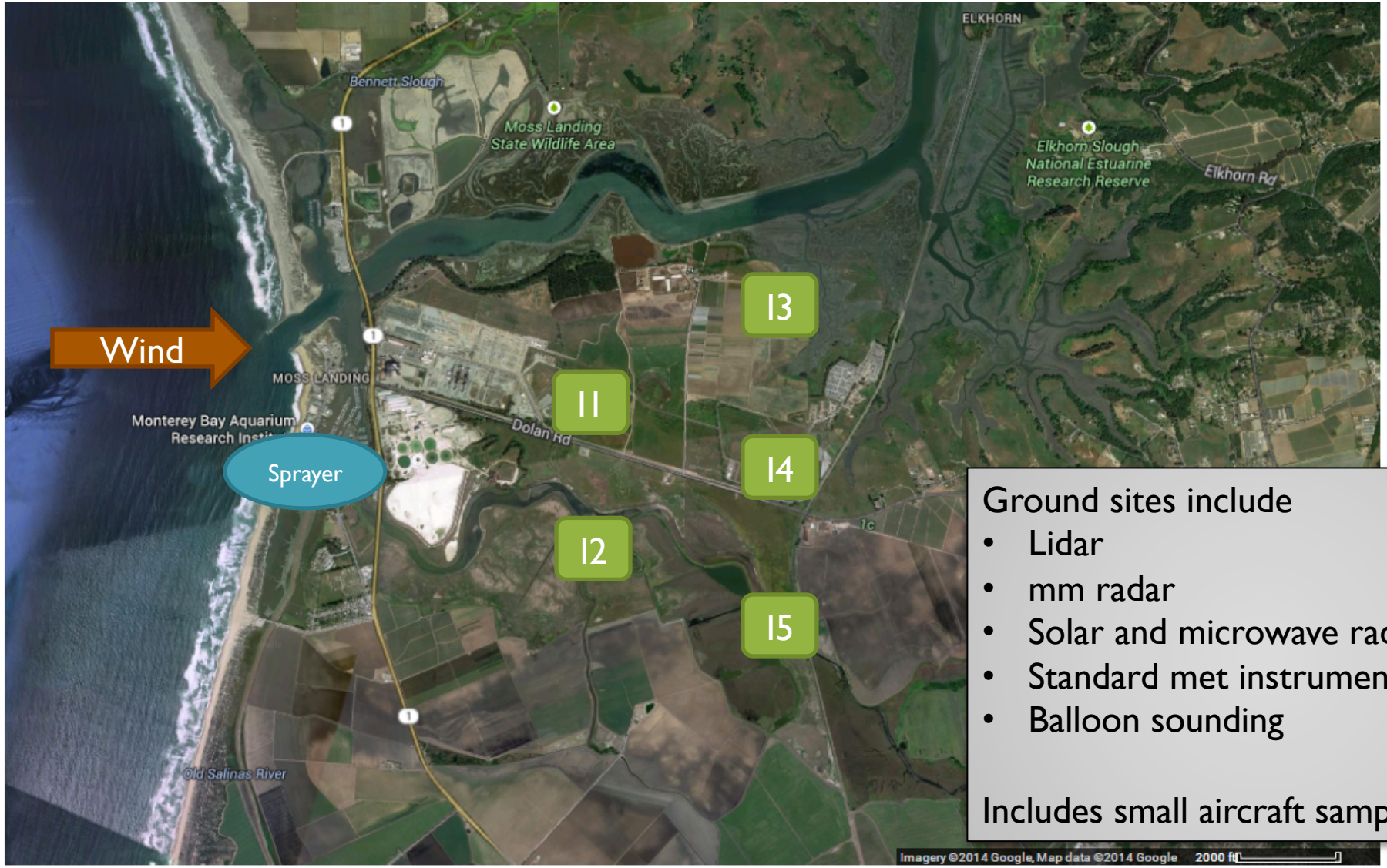


Phase 2

Testing with a scanning lidar system

Raman-shifted Eye-Safe Aerosol Lidar
California State University
Chico, CA

Phase 3: Testing a coastal environment



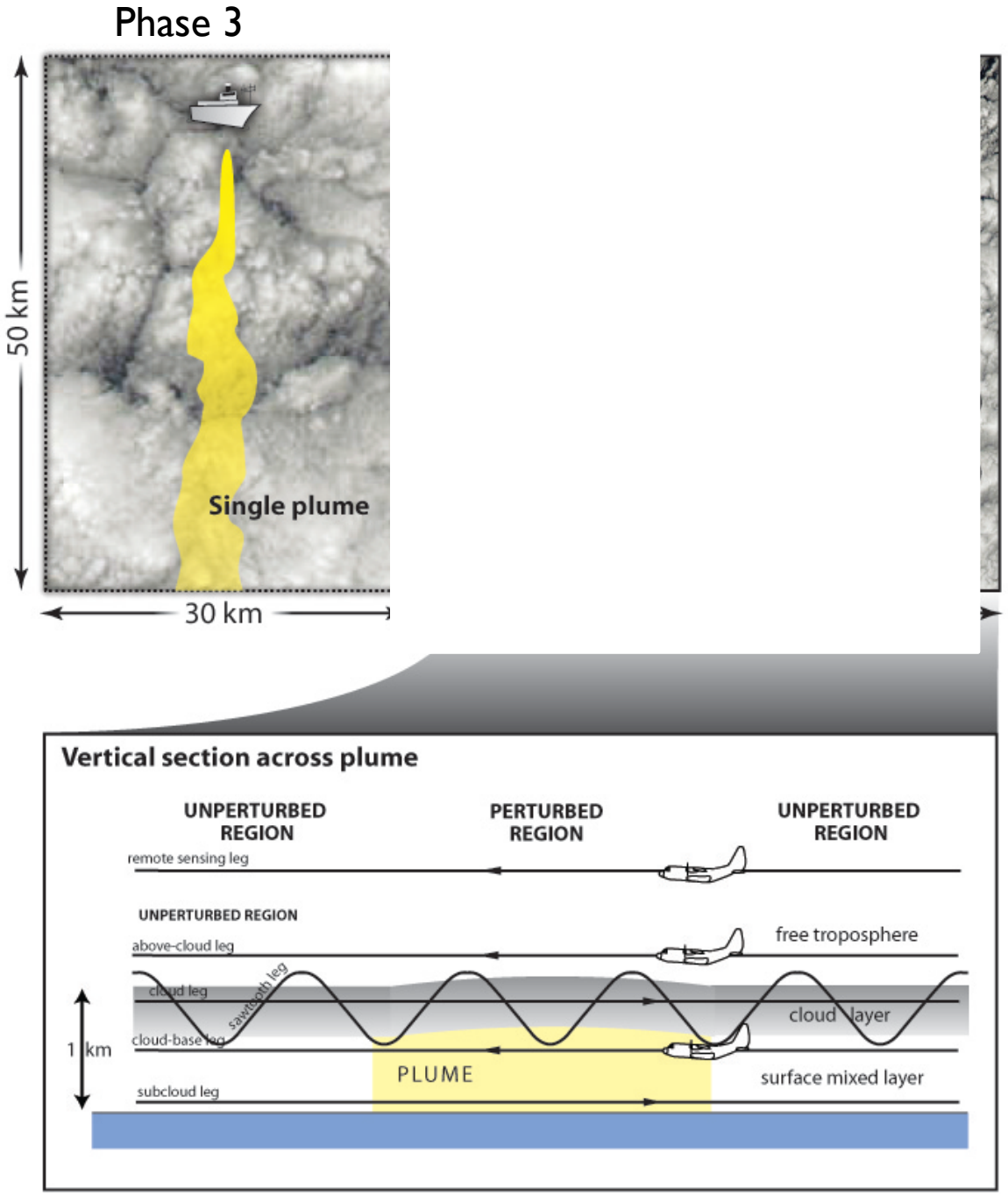
Ground sites include

- Lidar
- mm radar
- Solar and microwave radiometers
- Standard met instruments
- Balloon sounding

Includes small aircraft sampling

Open Ocean Testing

- Limited area perturbation experiment to critically test hypotheses related to aerosol indirect effects
- Phase 3
  - Single ship plume, possibly with multiple sprayers
  - Aircraft and ship sampling



Reframing the problem

Linkages

- Science is tied to ethics – some ethical arguments suggest no research on climate engineering should ever be done
- Science is tied to governance – any suggested experiment immediately brings calls for control and restriction
- Ethics is tied to science – different ethical arguments pertain to small-scale research, large-scale tests, and deployment
- Governance and ethics are highly linked – how to do it is coupled with what you think should be done

Some of the ethical issues

- Intent – advertent vs. inadvertent climate change
- Moral hazard – should we only do mitigation?
- Lesser of two evils – is climate engineering "better" than the alternative?
- Justice in our time – developed vs. developing countries
- Justice for future generations – what is our responsibility?
- What are the legal responsibilities? Who determines them?

A couple of sobering thoughts

- Solar radiation management does NOTHING to stop ocean acidification
  - Ocean will continue to grow more acidic with potentially very harmful effects to aquatic life starting at the bottom of the food chain
- Climate engineering CANNOT be started without a corresponding program to stop emissions
  - No way to stop CEng – if we stop, system will revert in a decade to temperatures we would have had without any CEng

And if you are wondering why I am presenting this in a CERES meeting?

nature climate change

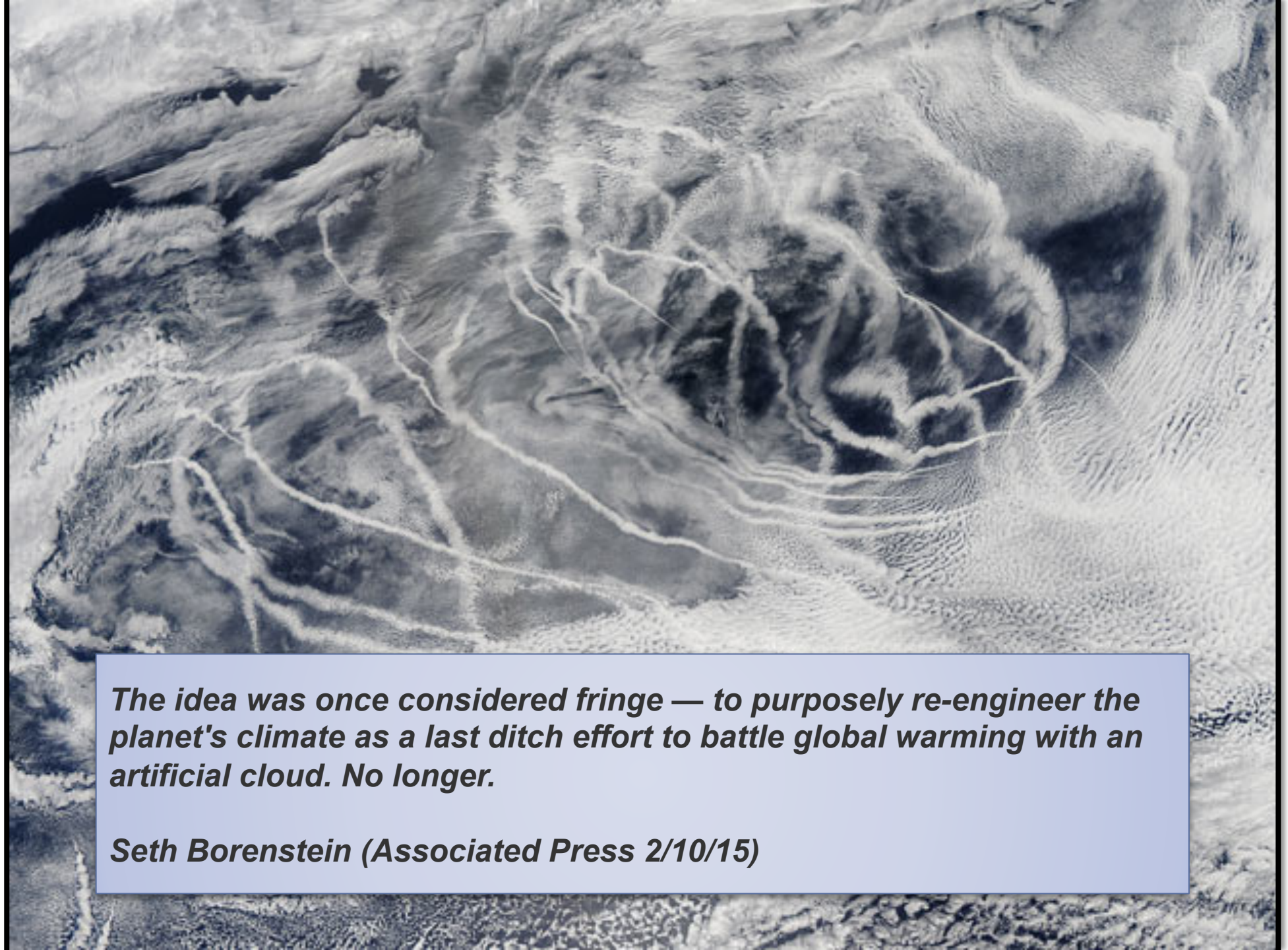
PERSPECTIVE

PUBLISHED ONLINE: 29 JANUARY 2014 | DOI: 10.1038/NCLIMATE2076

Detection limits of albedo changes induced by climate engineering

Dian J. Seidel[1]*, Graham Feingold[2], Andrew R. Jacobson[3] and Norman Loeb[4]

If we go down this path, measurement of TOA changes will be absolutely critical!



The idea was once considered fringe — to purposely re-engineer the planet's climate as a last ditch effort to battle global warming with an artificial cloud. No longer.

Seth Borenstein (Associated Press 2/10/15)