Fighting Climate Change By Engineering Air Pollution To Brighten Clouds

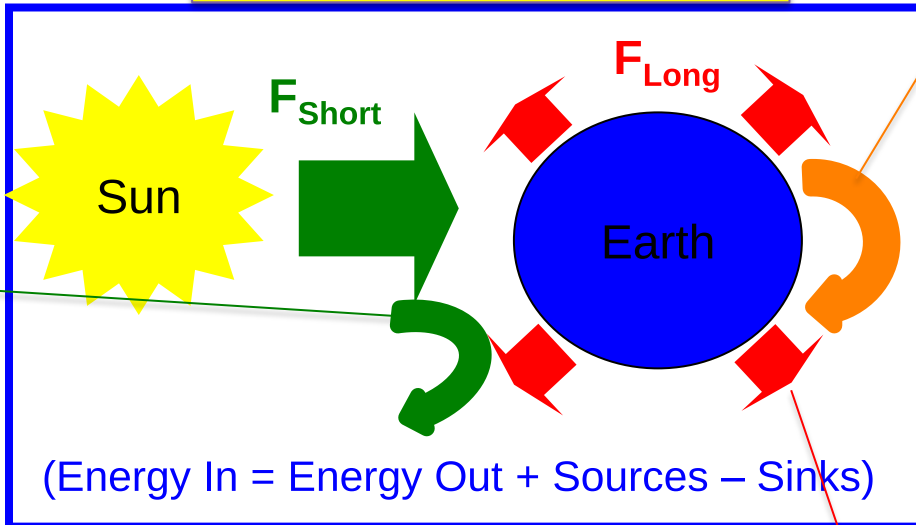
Lynn M. Russell

Scripps Institution of Oceanography

http://aerosols.ucsd.edu/

Earth's "Energy Balance"

$S_0(1-\alpha_p) + F_{ghg} = \sigma T_{surf}^4$



Aerosol-enhanced albedo effect
$F_{Short} = S_0(1-\alpha_p)$

- Hilding Köhler 1936
- Sean Twomey 1974

CO_2-enhanced greenhouse effect

- Joseph Fourier 1824
- John Tyndall 1858
- Svante Arrhenius 1896

1st Law of Thermodynamics
$F_{Short} = F_{Long}$

- Rudolf Clausius 1850
- William Thompson (Lord Kelvin) 1848

Stefan-Boltzmann Law
$F_{Long} = \sigma T_{surf}^4$

- Josef Stefan 1874
- Ludwig Boltzmann 1884
- Max Planck 1901

Global Mean Temperature “Model”

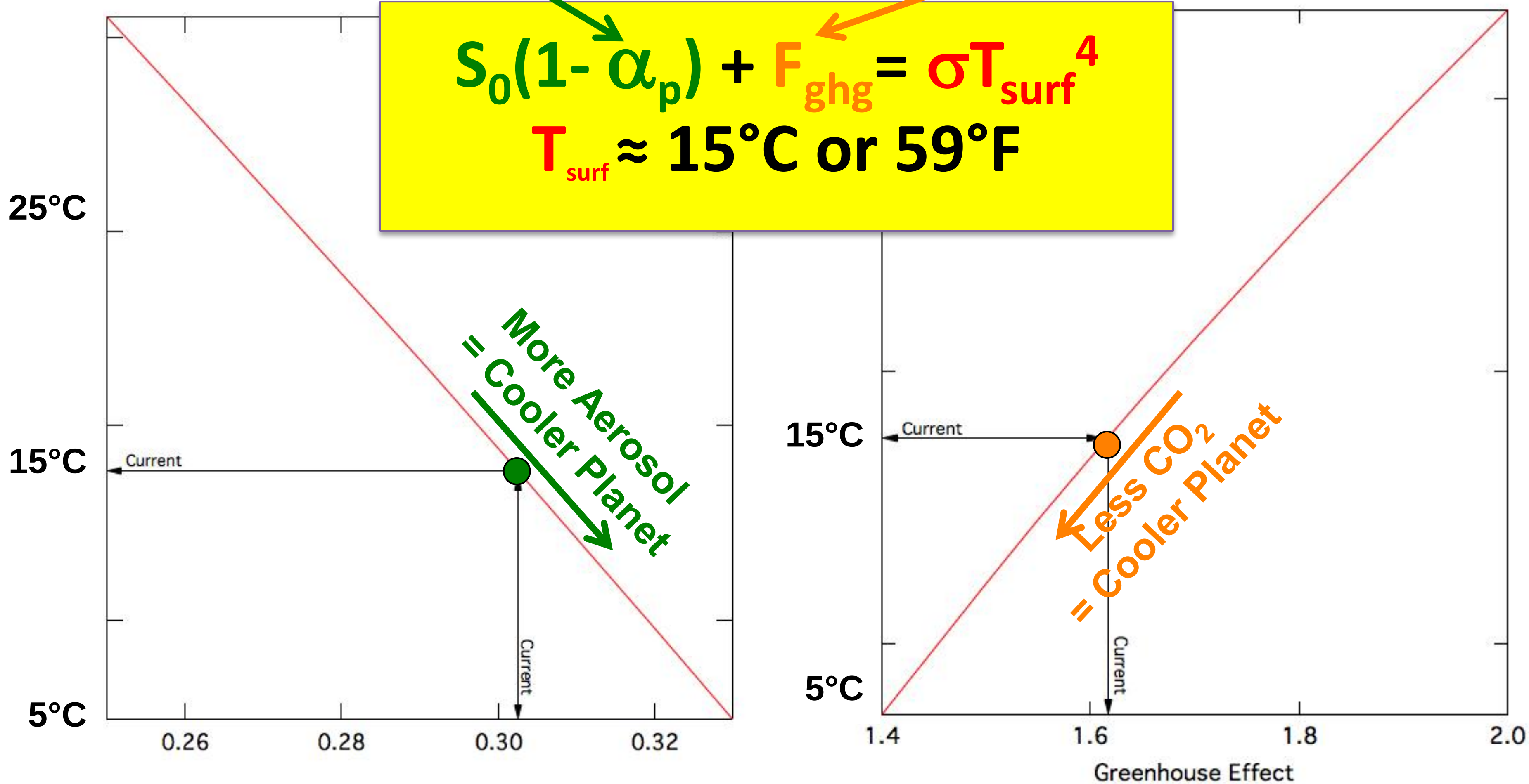
(N.B. Does Not Address Regional+Precipitation Changes)

↑ Albedo Effect (Sunlight Reflection Methods – SRM)

↓ Greenhouse Effect (Carbon Dioxide Removal – CDR)

$$S_0(1-\alpha_p) + F_{ghg} = \sigma T_{surf}^4$$

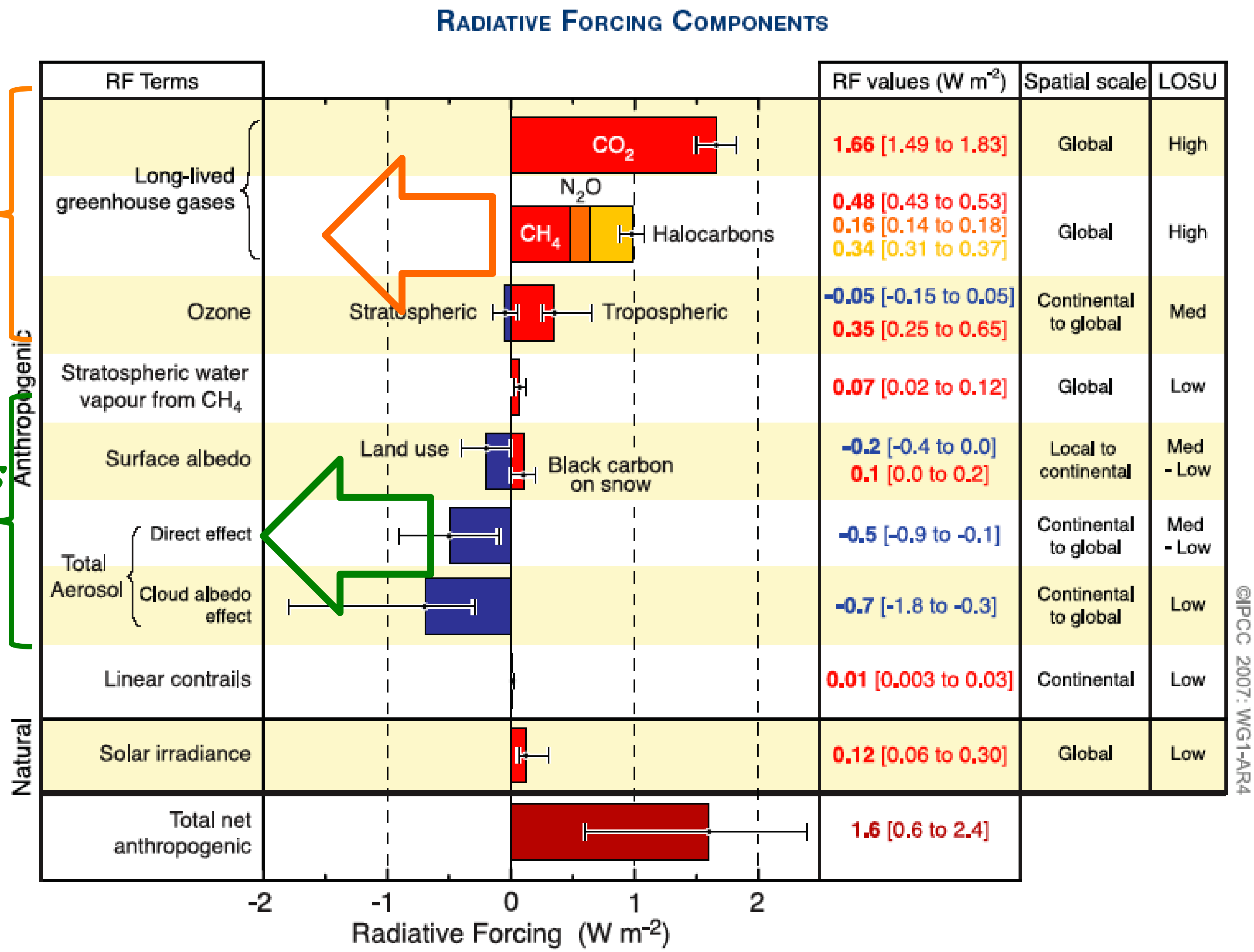
$$T_{surf} \approx 15°C \text{ or } 59°F$$



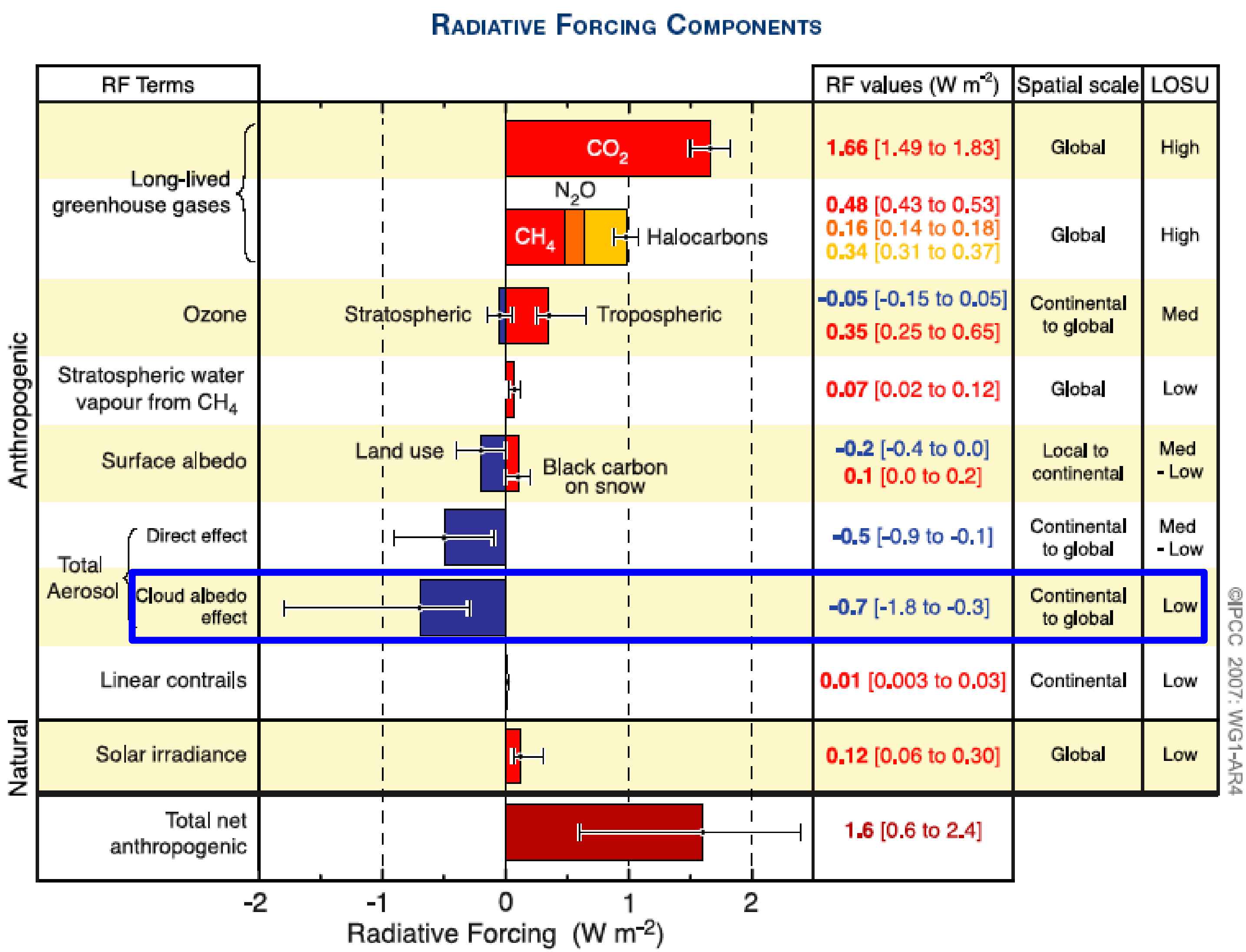
Carbon Dioxide Removal (CDR) vs. Solar Radiation Management (SRM)

CDR reduces greenhouse gases

SRM increases albedo components



Carbon Dioxide Removal (CDR) vs. Solar Radiation Management (SRM)



- Introduction to Aerosol Effects on Clouds and Historical Context

- Recent Model Simulations of Cloud Brightening

- New Experimental Evidence of Cloud Brightening

- Implications For Climate Engineering

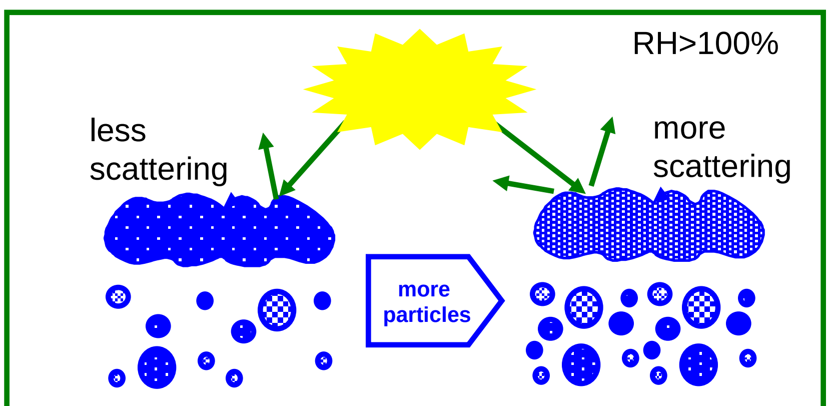
POLLUTION AND THE PLANETARY ALBEDO

S. Twomey

Institute of Atmospheric Physics, The University of Arizona, Tucson, Arizona 85721, U.S.A.

(*First received* 27 *February* 1974 *and in final form* 17 *May* 1974)

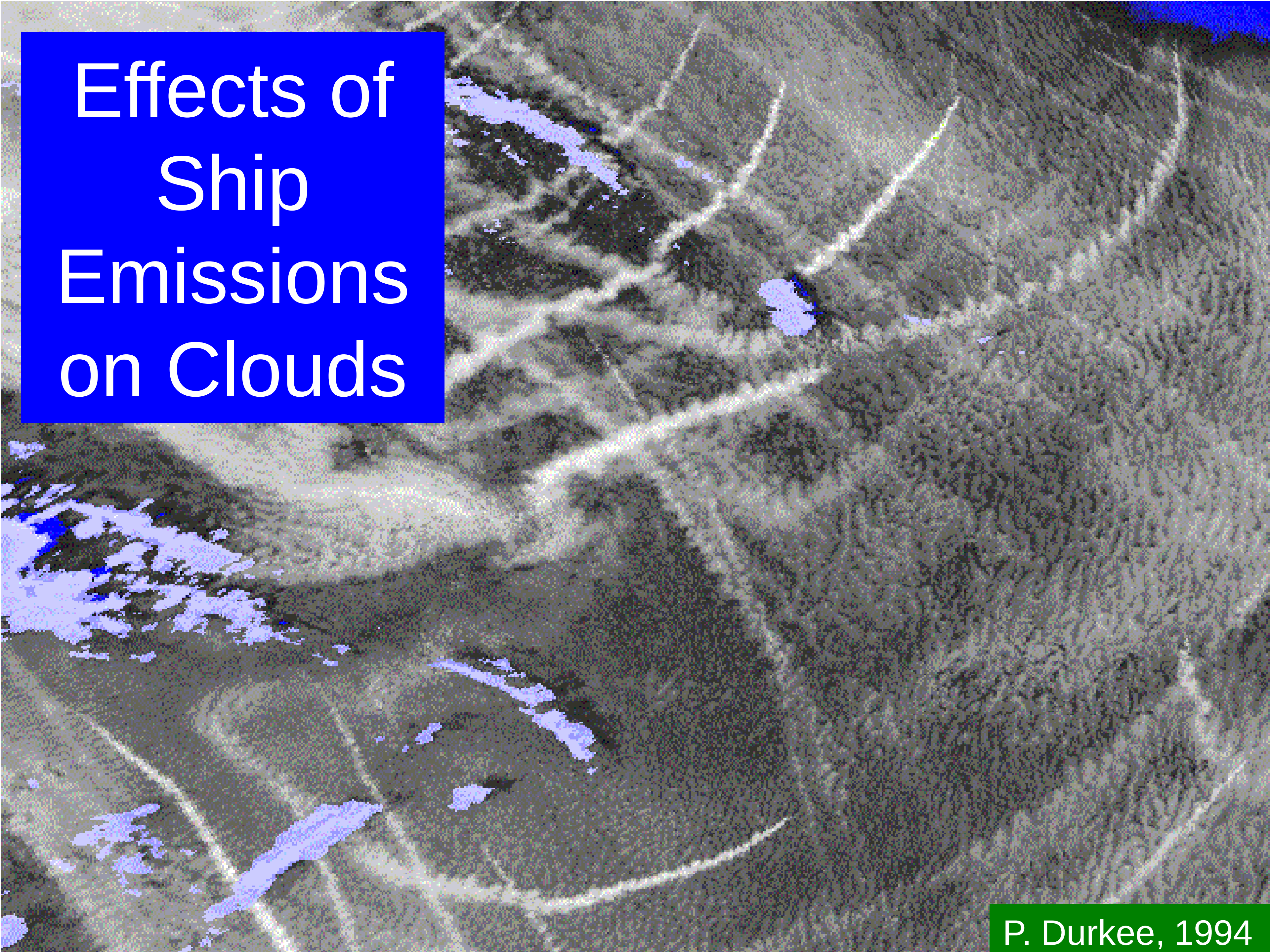
Abstract—Addition of cloud nuclei by pollution can lead to an increase in the solar radiation reflected by clouds. The reflection of solar energy by clouds already may have been increased by the addition of man-made cloud nuclei. The albedo of a cloud is proportional to optical thickness for thin clouds, but changes more slowly with increasing thickness. The optical thickness is increased when the number of cloud nuclei is increased. Although the changes are small, the long-term effect on climate can be profound.



Cloud albedo effect:

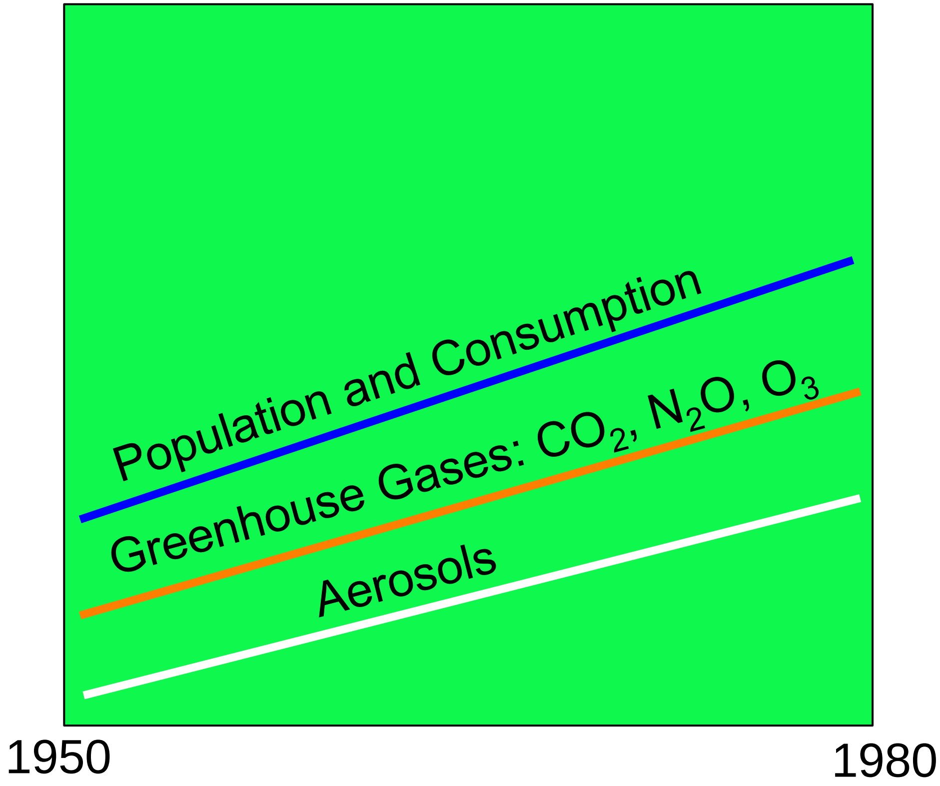
More droplets → increased reflectance

Effects of Ship Emissions on Clouds



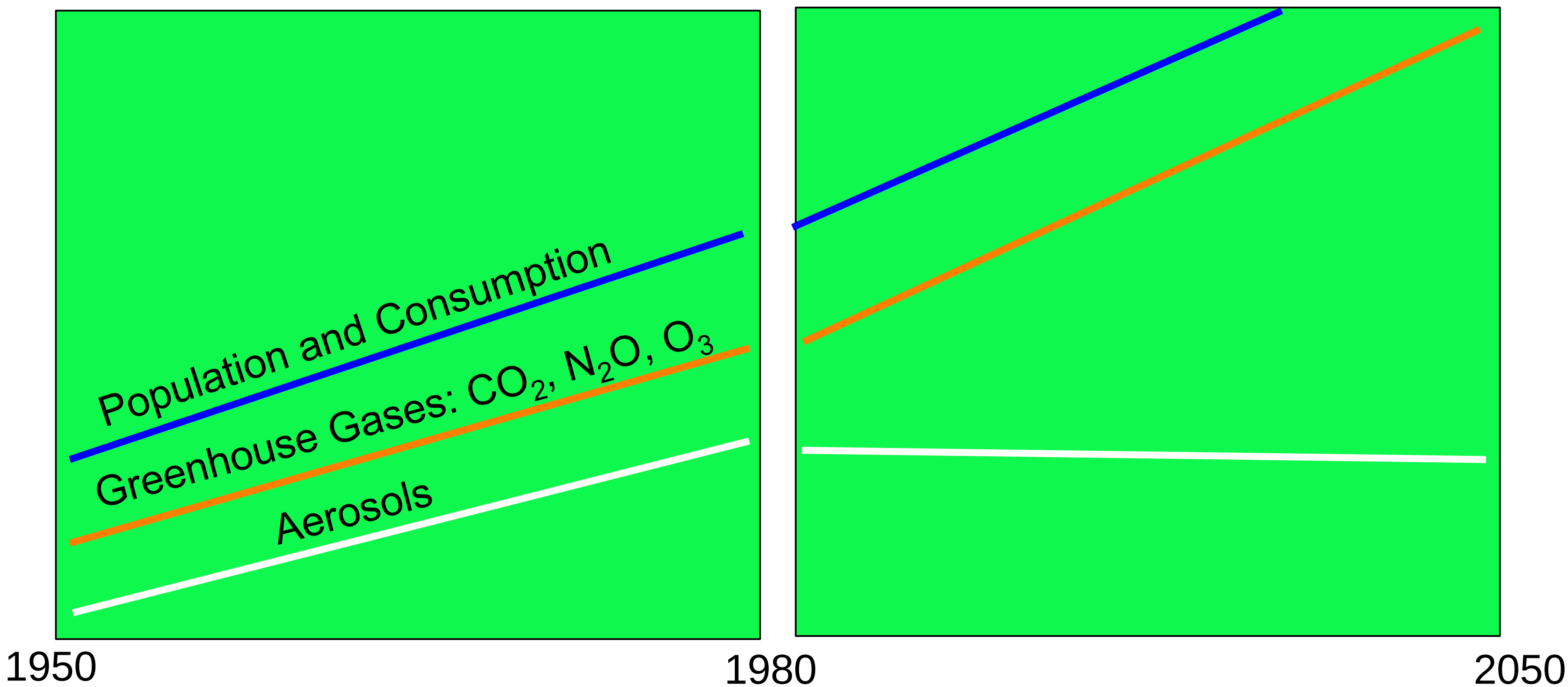
P. Durkee, 1994

Historical Context:
Combustion Emission Trends



- Fossil fuel usage and biomass burning have increased with human population, resulting in increased greenhouse gas and aerosol emissions

Historical Context: Combustion Emission Trends



- Fossil fuel usage and biomass burning have increased with human population, resulting in increased greenhouse gas and aerosol emissions

- However, in industrialized nations the emission of scattering aerosols has been Engineered to improve air quality.

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- **Recent Model Simulations of Cloud Brightening**
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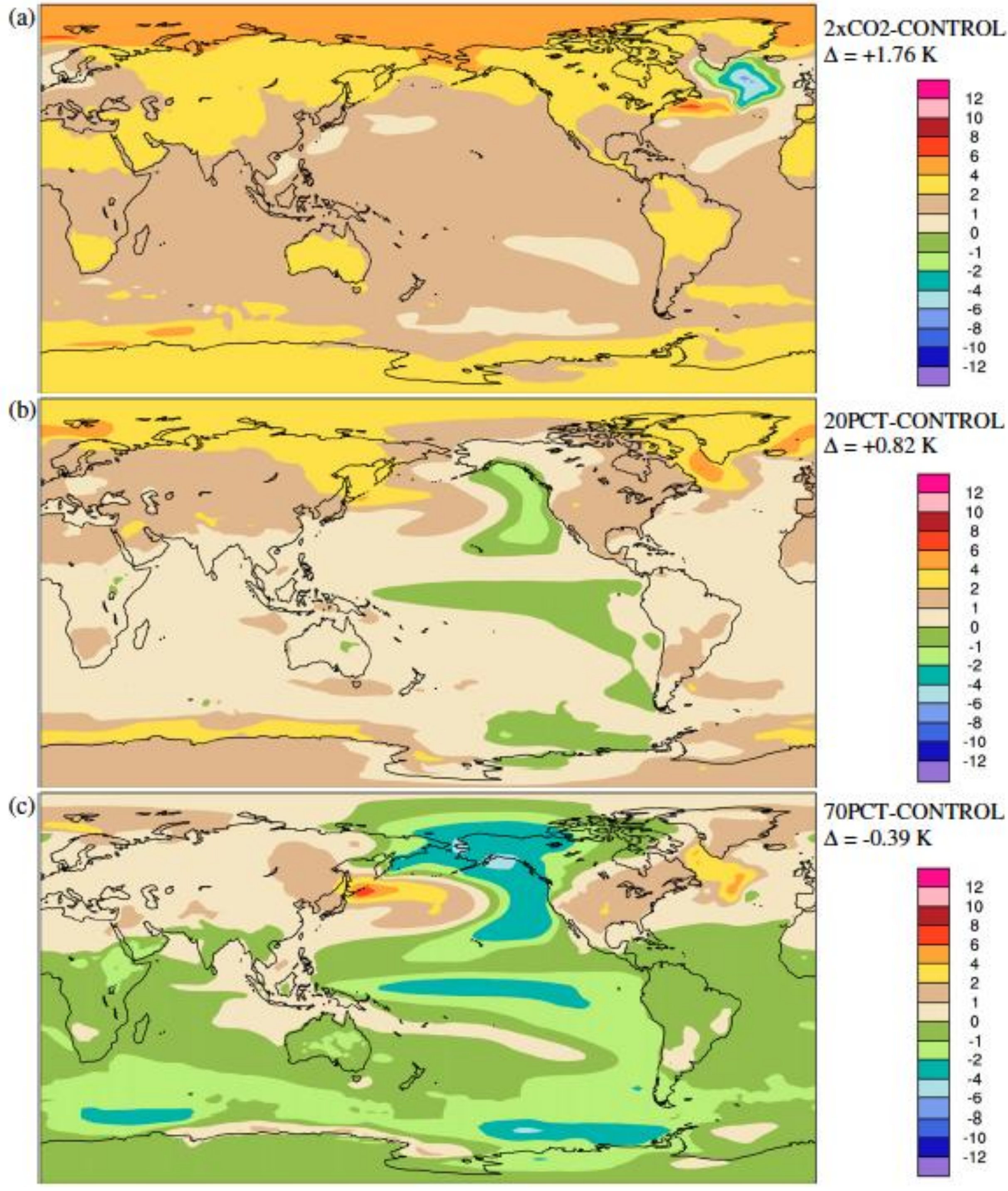
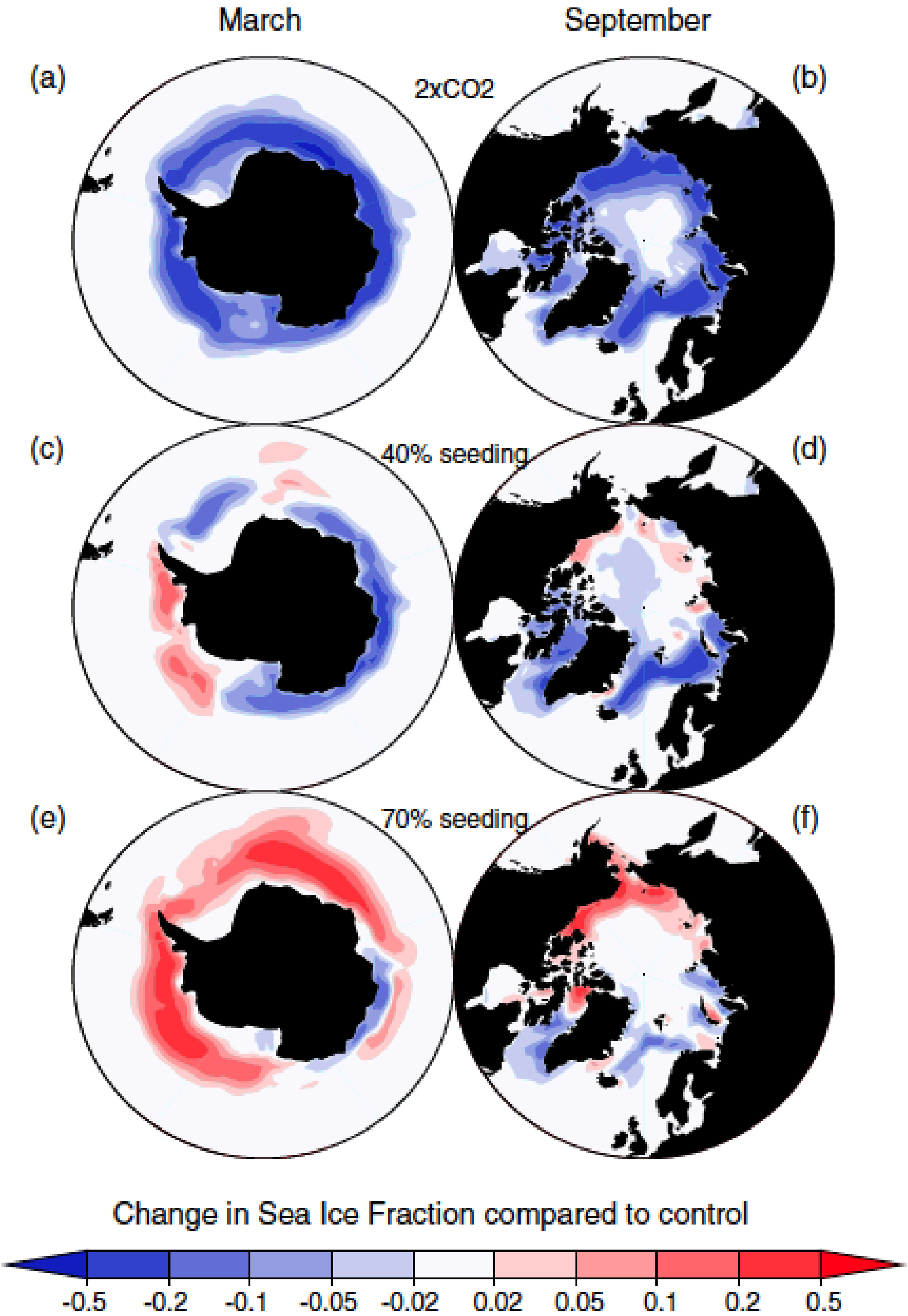
Proposed Cloud "Seeding"



20% increase shows some cooling but no excessive cooling; 70% shows excessive cooling over Pacific.

Rasch et al., 2009

Predicted Changes in Polar Sea Ice



To offset most sea ice reduction in Arctic, need 70% seeding.

Rasch et al., 2009

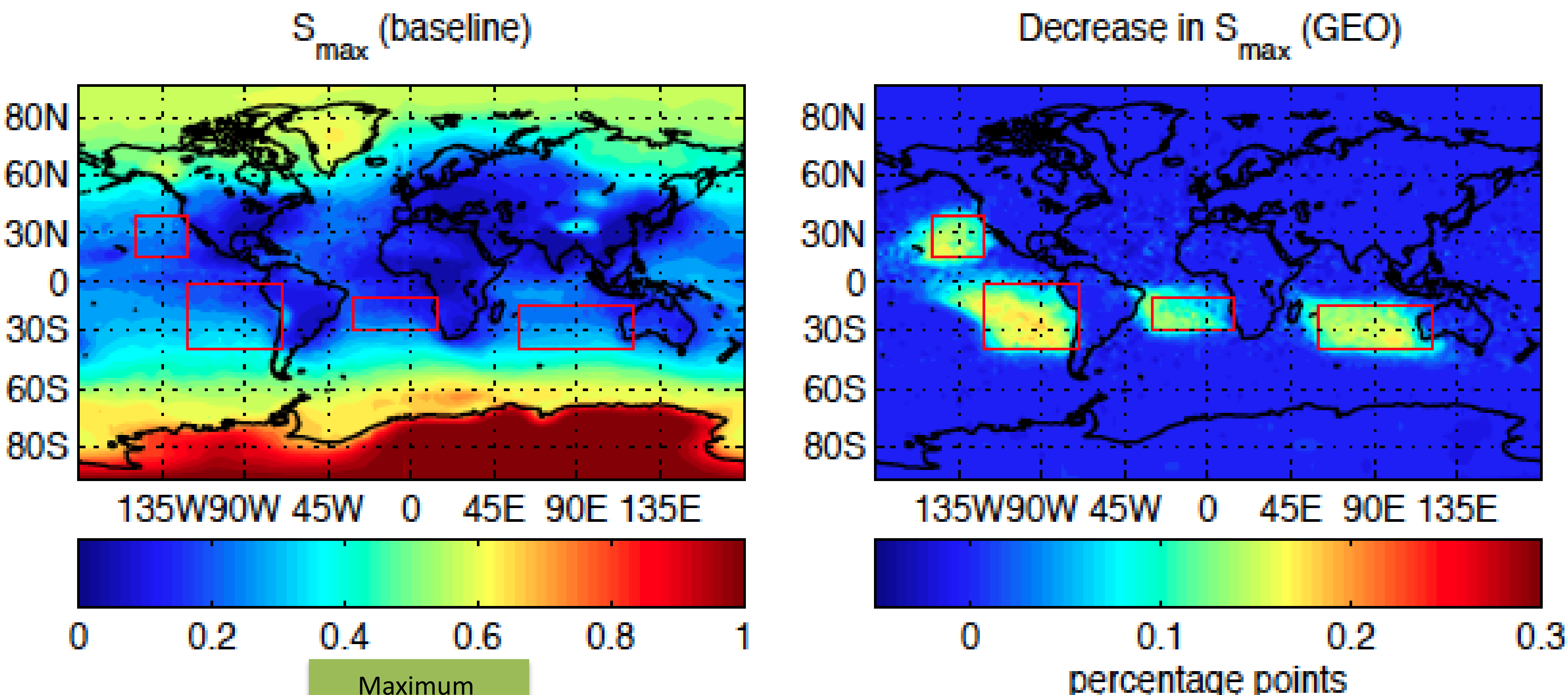
But, how certain is this result?

Environ. Res. Lett. 4 (2009) 045112

lifetime may be modified by other processes that counteract the influence of increases to CCN [12–19]. These numerical simulations of marine stratocumulus and trade wind cumulus clouds revealed some situations where nonlinear dynamical responses to increasing CCN actually decreased cloud liquid water content and either decreased or did not change the albedo. It is clearly critical to our geoengineering strategy that these nonlinear interactions be understood, quantified, and verified and their relative importance compared to the Twomey effect be assessed. A better understanding of cloud microphysics and dynamics is required before we will know under what circumstances increasing the CCN number will indeed increase the planetary albedo. This understanding will be achieved eventually through a combination of fieldwork and improvements to our theoretical understanding and modelling of clouds.

Why is Response Nonlinear?

- In addition to adding new nuclei, particles change the rate at which water condenses, which changes the maximum cloud "supersaturation" (Relative Humidity – 100%)



Maximum Supersaturation (RH-100)%

Korhonen et al., 2010

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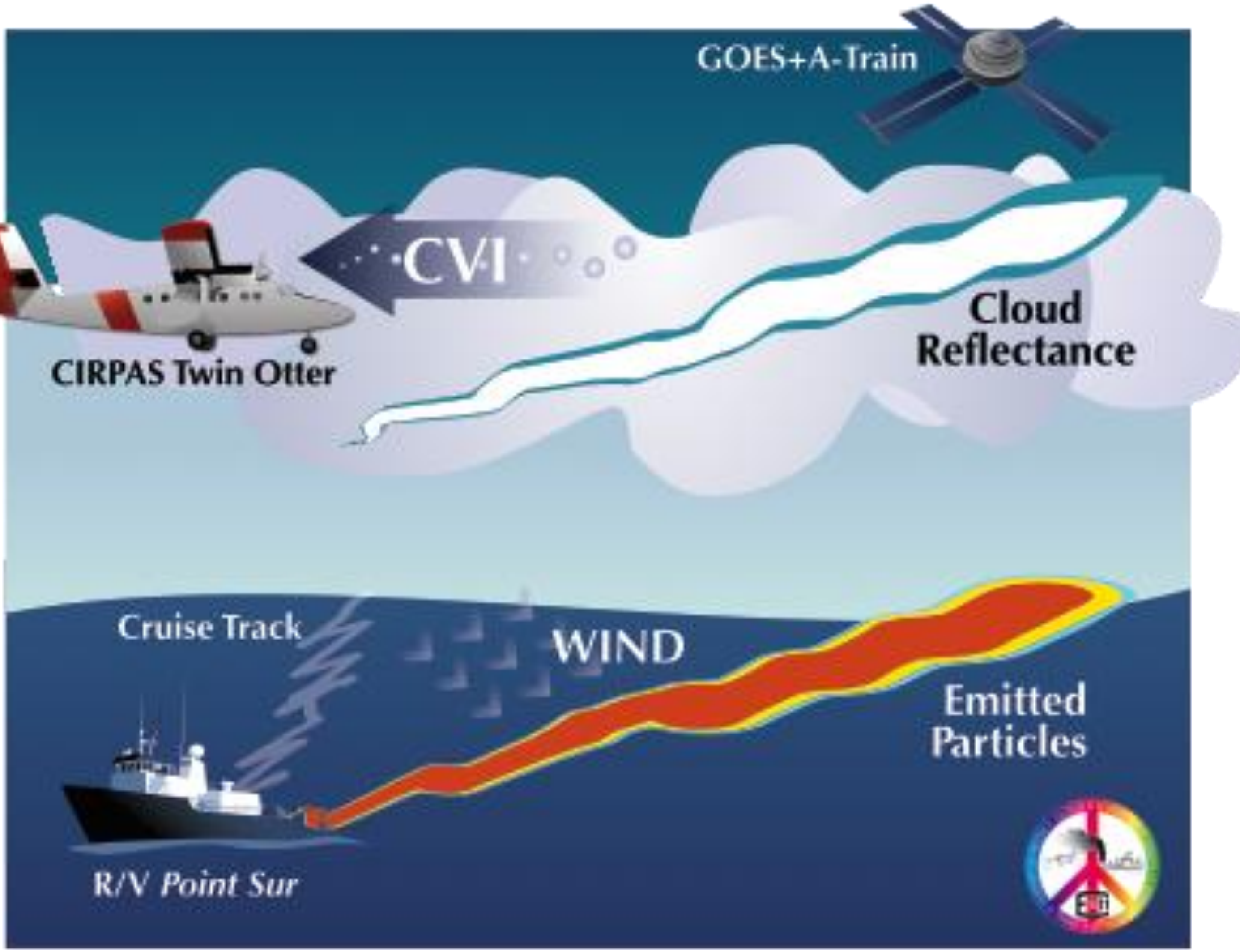
Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011



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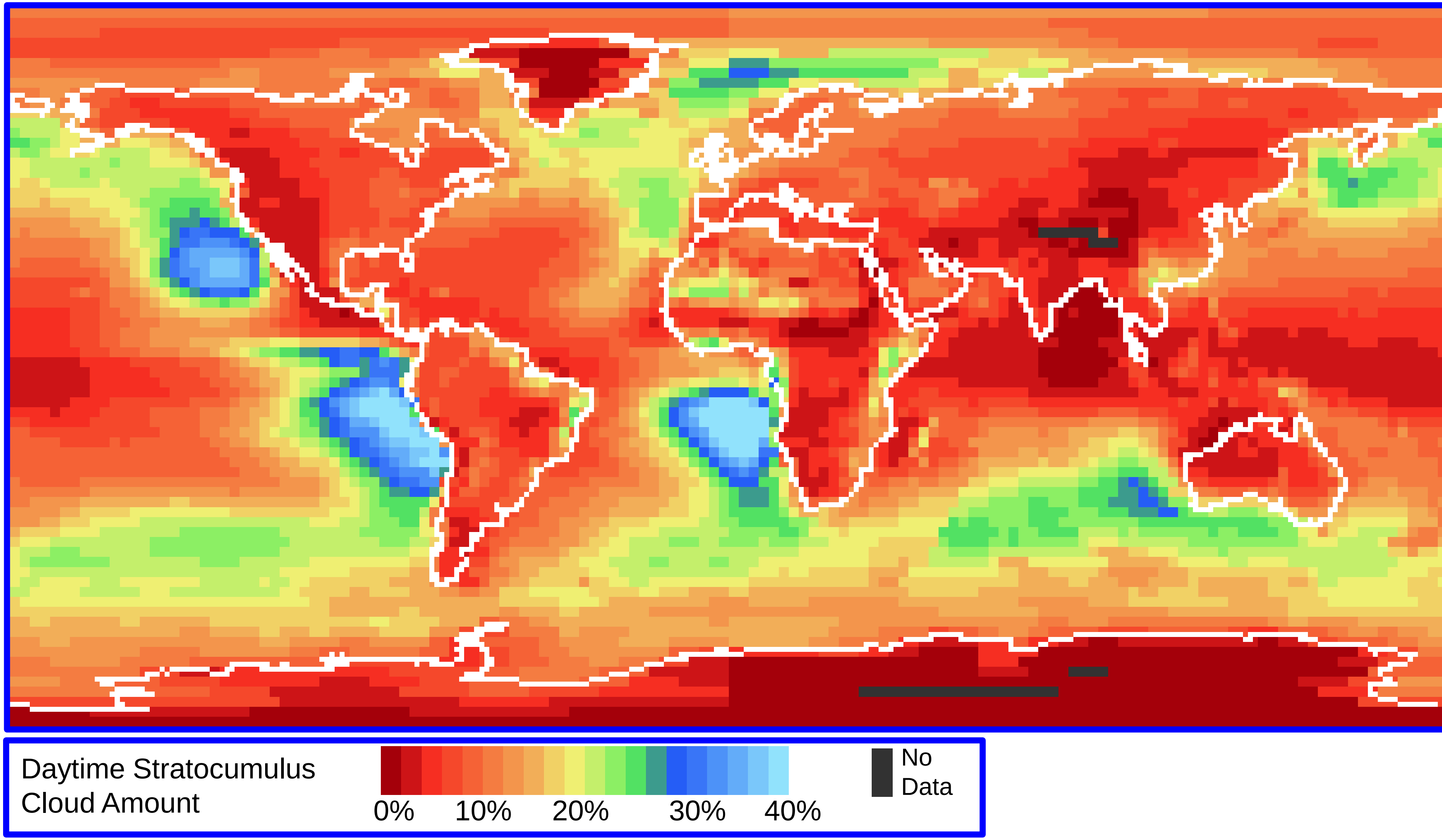
1.Scripps/UCSD, 2.Caltech, 3.Univ.Arizona, 4.GeorgiaTech, 5.Univ.Miami, 6.CIRPAS.

Where is highest Sc probability?



Prior Use of Paraffin Oil Smoke for Plume Dispersion Studies

Studies of Atmospheric Diffusion from a Nearshore Oceanic Site[1]

GILBERT S. RAYNOR, PAUL MICHAEL, ROBERT M. BROWN AND S. SETHURAMAN

Brookhaven National Laboratory, Upton, N. Y. 11973

(Manuscript received 26 July 1974, in revised form 20 January 1975)

ABSTRACT

A research program is in progress at Brookhaven National Laboratory to determine the nature of atmo-
spheric diffusion from a representative oceani
and oceanographic variables, and to develop r
in response to plans for construction of offsho
Tracer experiments are conducted utilizing
shore during onshore flows. The smoke is pho
and vertical spread. The crosswind concentra

FIG. 2. Landing craft, Model LCM-8, emitting oil-fog smoke.

R/V *Point Sur* Smoke Operations

U.S. Army "Smoke/Fog Generator"
ca. 1980 for "battlefield obscuration"
E-Bay price: $100 ea.

Shell Diala $10/gal
Sponsored by

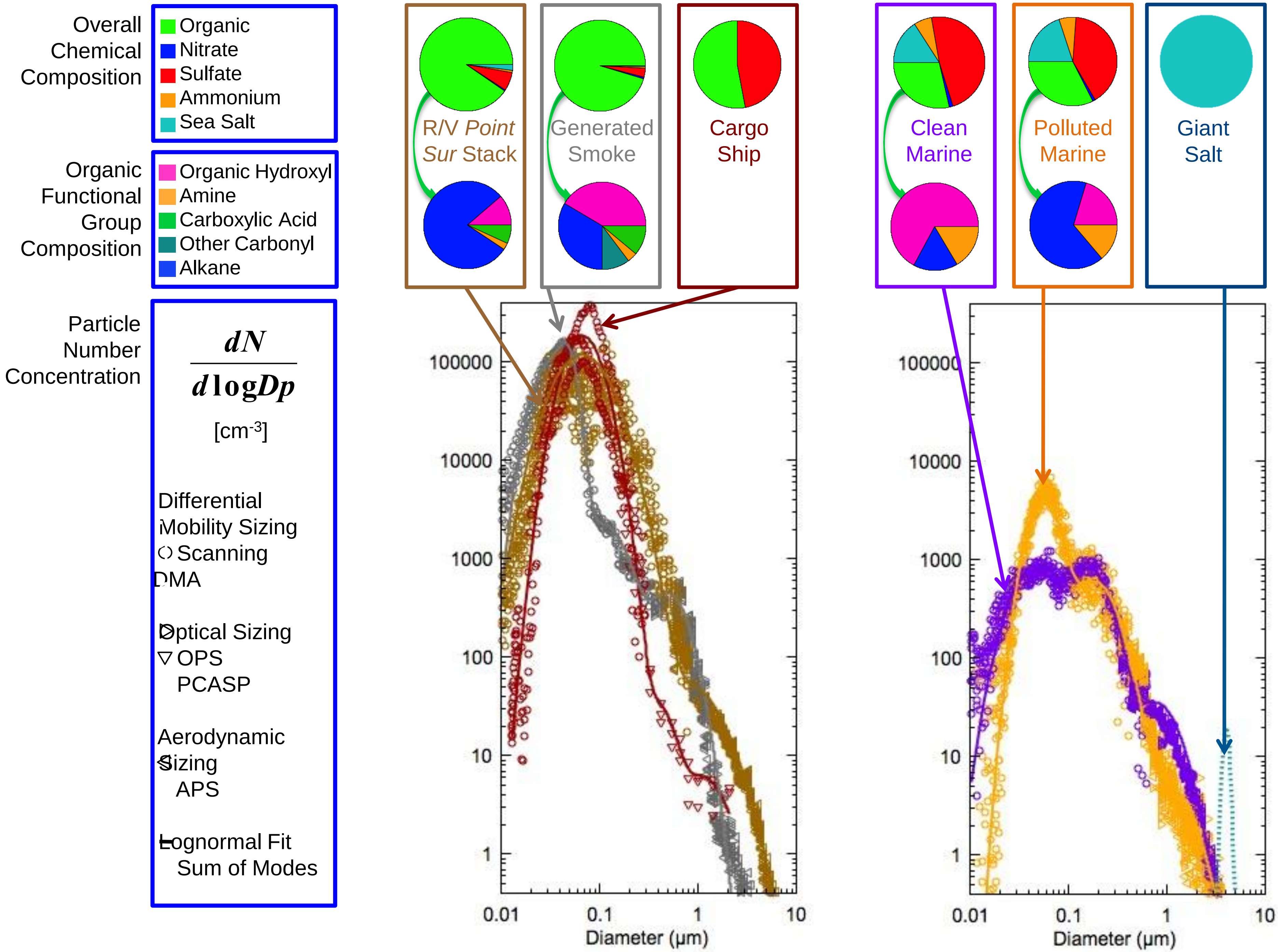
SEA SPRAY RESEARCH FOUNDATION

R/V *Point Sur* Smoke Operations

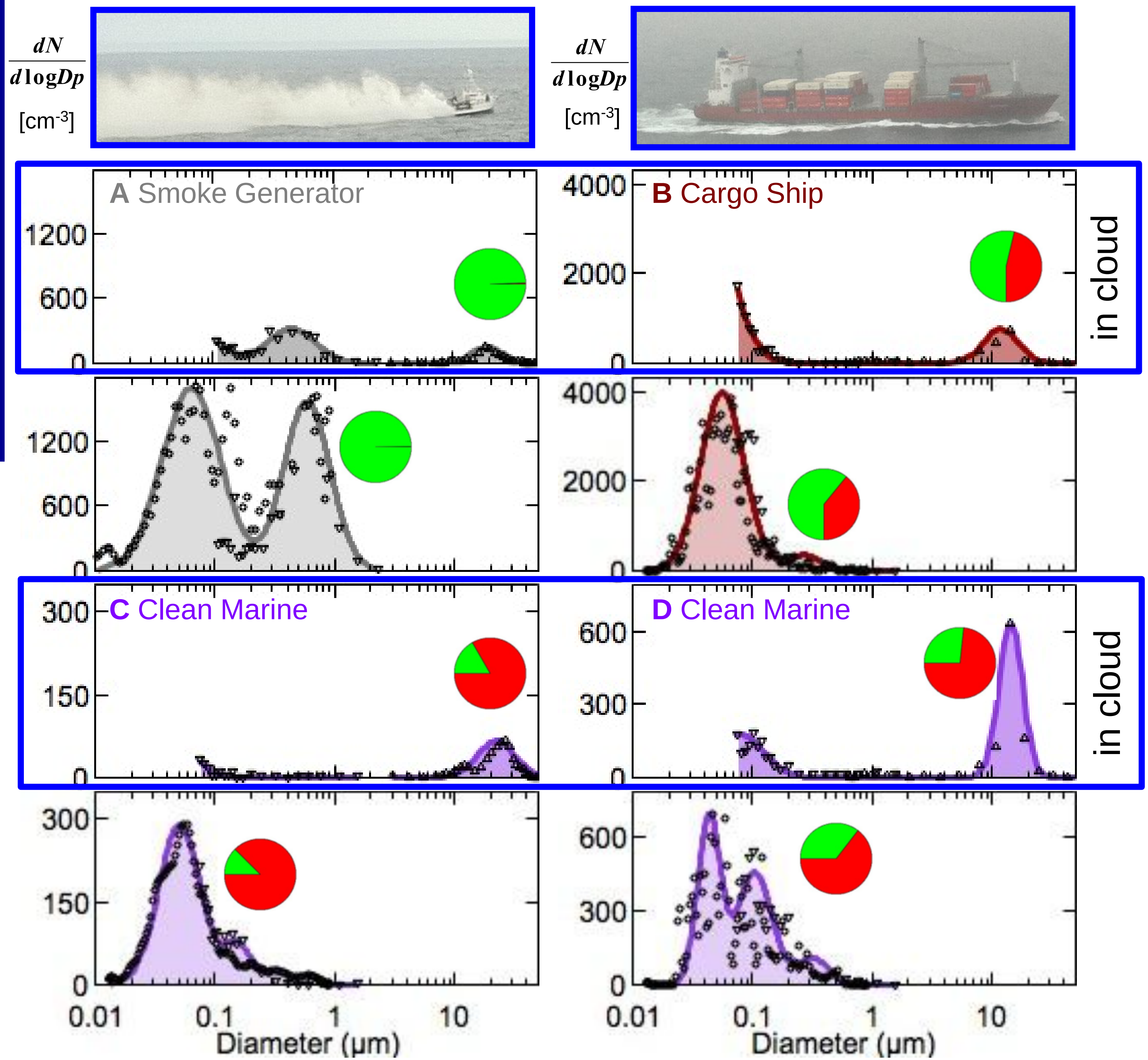
CIRPAS Twin Otter Measurements of Smoke from R/V *Pt Sur*

Three Parts of Engineering Clouds

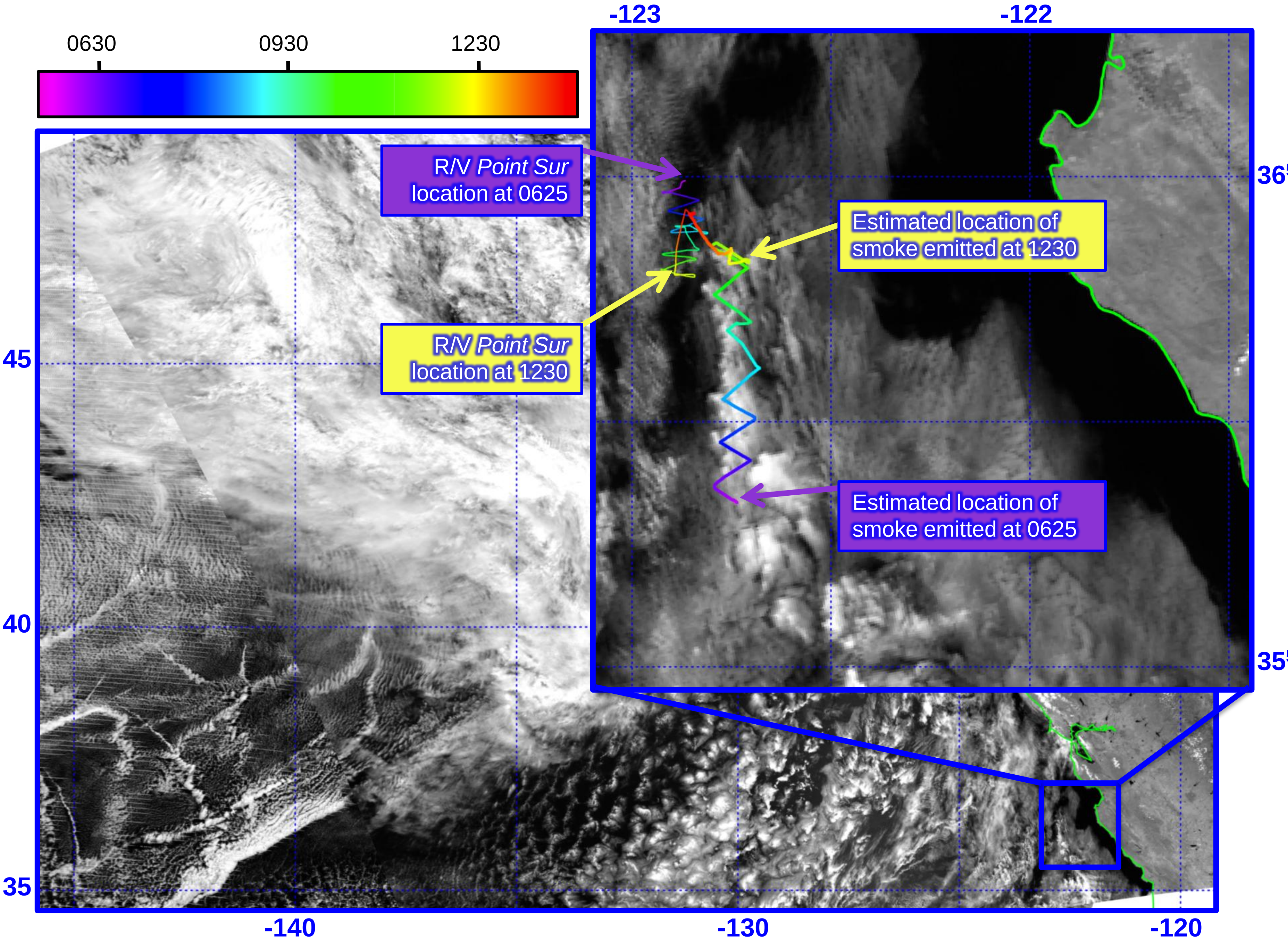
- Did we produce enough smoke particles?
- Do smoke particles make cloud droplets?
- Do the droplets change albedo?


Overall Chemical Composition
Organic
Nitrate
Sulfate
Ammonium
Sea Salt
Organic Functional Group Composition
Organic Hydroxyl
Amine
Carboxylic Acid
Other Carbonyl
Alkane
Particle Number Concentration
$\frac{dN}{d\log Dp}$
[cm^{-3}]
Differential Mobility Sizing
Scanning DMA
Optical Sizing
OPS
PCASP
Aerodynamic Sizing
APS
Lognormal Fit
Sum of Modes
R/V Point Sur Stack
Generated Smoke
Cargo Ship
Clean Marine
Polluted Marine
Giant Salt
100000
10000
1000
100
10
1
0.01
0.1
1
10
Diameter (µm)
100000
10000
1000
100
10
1
0.01
0.1
1
10
Diameter (µm)

Do Smoke Particles Act as Cloud Droplets?



- Organic
- Nitrate
- Sulfate
- Ammonium
- Sea Salt



0630
0930
1230
-123
-122
36^5
35^5
R/V Point Sur location at 0625
Estimated location of smoke emitted at 1230
R/V Point Sur location at 1230
Estimated location of smoke emitted at 0625
45
40
35
-140
-130
-120

Three Parts of Engineering Clouds

- Did we produce enough smoke particles?
  - Yes.
- Do smoke particles make cloud droplets?
  - Yes.
- Do the droplets change albedo?
  - Sometimes. How often?

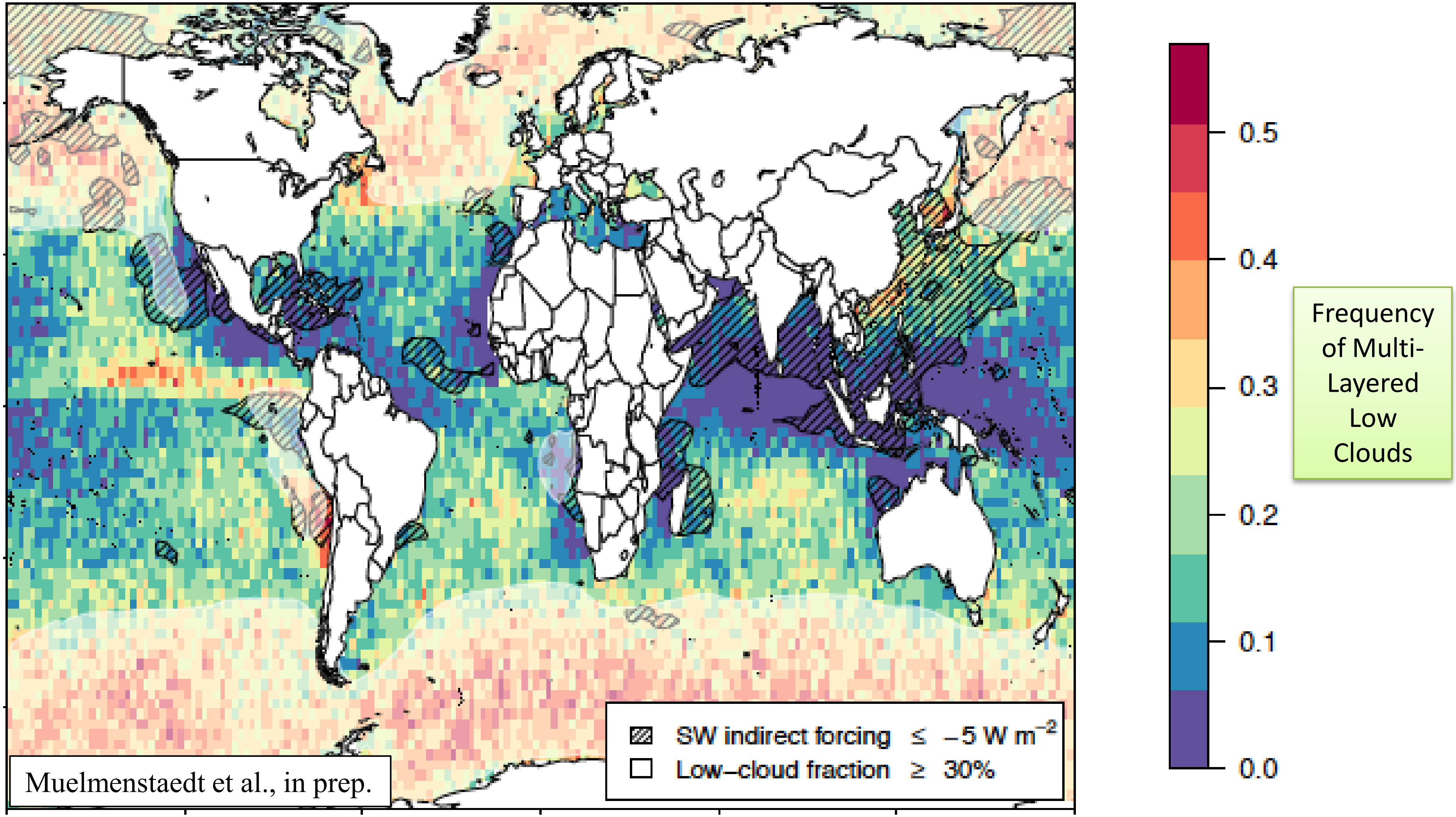
Why Did So Few Tracks Form?

	Tracks Observed	Clear or Scattered	Multi-Layered[1]	High or Raining[2]
July 1-31 (2011) in region	22 days	0 days	NK	NK
July 12-23 (2011) in region	4 days	variable	NK	NK
July 12-23 (2011) at ship	1 day	2 days	$\boxed{\text{7 days}}$	2 days

The region near the ship had multi-layered clouds 7 out of 12 days; particles don't mix up to the top layer so tracks don't form on these days.

How important is this effect **globally** for cloud albedo forcing?

Multi-Layered Cloud Frequency Reduces Cloud Albedo Effects



- Seeding clouds doesn't "work" if there are other clouds above them

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This was not a geoengineering experiment, but it is worth noting that…

Two man-made technologies have demonstrated an observable cooling

- Cargo ships
  - Price: $100k/dy
  - 100k gal bunker/dy burned
    - 1 nK warming from CO_2
    - 2 nK cooling from CDN
  - Cooling/Warming ~ 2 (±1)

- R/V *Pt Sur* with smoke generators
  - Price: $15k/dy
  - 500 gal diesel/dy burned
    - 0.008 nK warming from CO_2
  - 200 gal oil/dy
    - 0.4 nK cooling from CDN
  - Cooling/Warming ~ 50 (±20)

Assumptions: 100-yr time horizon, scaled to climate sensitivity of IPCC [2007] median value (i.e. 3K per 280 ppmv); 15% increase in reflectivity for track on 16 July; assume track persists in daylight for 6 hr normalized by 100 years.

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Geoengineering

Implicit promises

A geoengineering experiment has come unstuck. But there will be more

May 19th 2012

FOR the past
of Novel Optic
engineer the
surface. A lot
computer mo
veils of reflect
oceans.

The meeting in Mainz also learned, though, of another experiment that has met with better fortune. Last September a team led by researchers from the Scripps Institution of Oceanography, in La Jolla, California, looked at whether clouds could be whitened artificially (and thus caused to reflect more sunlight back into space) using particles emitted from a boat. Such brightening has been observed in the exhaust plumes of cargo ships for some time, but Lynn Russell, who ran the experiment, was still surprised by how much brightening the team saw. Though Dr Russell's experiment had been designed mainly to look at how clouds form naturally, it paves the way for future work on geoengineering. How that will affect attitudes to global warming remains to be seen.

Related topics

Environmental problems and protection

Climate change

Nature and the environment

Science

Engineering

Brightening clouds “works” (to offset some warming)

- Organic particles are effective nuclei for cloud droplets[1]
- Increased droplet numbers increases albedo
- Technology for seeding exists at low CO_2 cost (~20x)[2]
- Observations show competing, nonlinear effects.

But it’s complicated (so scale up is uncertain)

- Ecosystem impacts of smoke have not been investigated[3]
- Frequency less than predicted by climatology
  - Multi-layered clouds[4]
- GCMs do not have key processes and variability
- Experiments are needed to provide scale-up testing.

[1]Shingler et al., 2012, *Atmo. Chem. Phys.*

[3]Russell et al., 2012, *AMBIO*
[4]Muelmenstaedt et al., 2012, in prep

Review

Engineering geo-engineering

Timothy A. Fox[a]* and Lee Chapman[b]

[a] *Institution of Mechanical Engineers, London, SW1H 9JJ, UK*

[b] *School of Geography, Earth and Environmental Science, University of Birmingham, Birmingham, B15 2TT, UK*

ABSTRACT: This paper reviews the geo-engineering approach to tackling climate change. The failure of the 15th United Nations Framework Convention on Climate Change Conference o
reduction agreement makes the deployment of geo-engineering s
looks at a variety of global and local approaches to geo-engi
cycle engineering and attempts to assess the feasibility of the
despite the plethora of ideas generated by the science commun
the initial engineering assessment of these techniques and this i
scheme can be fully considered. Hence, the paper concludes b
programmes of research at the feasibility level, to inform discus
local geo-engineering and adaptation measures. Copyright © 20

Table I. Initial ranking of engineering feasibility of schemes described in this paper for deployment at an appropriate scale (those in italics require international agreement).

↓ Decreasing engineering feasibility, from feasible (top) to unfeasible (bottom)	Reforestation/afforestation
	Aerosols
	Carbon capture: marine sequestration
	Ocean fertilization
	Carbon capture: geological sequestration
	Increased ocean alkalinity
	Biochar
	Albedo management
	Algae on buildings
	Spaceborne solar reflectors

CIRPAS Twin Otter Measurements of Smoke from R/V *Pt Sur*

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