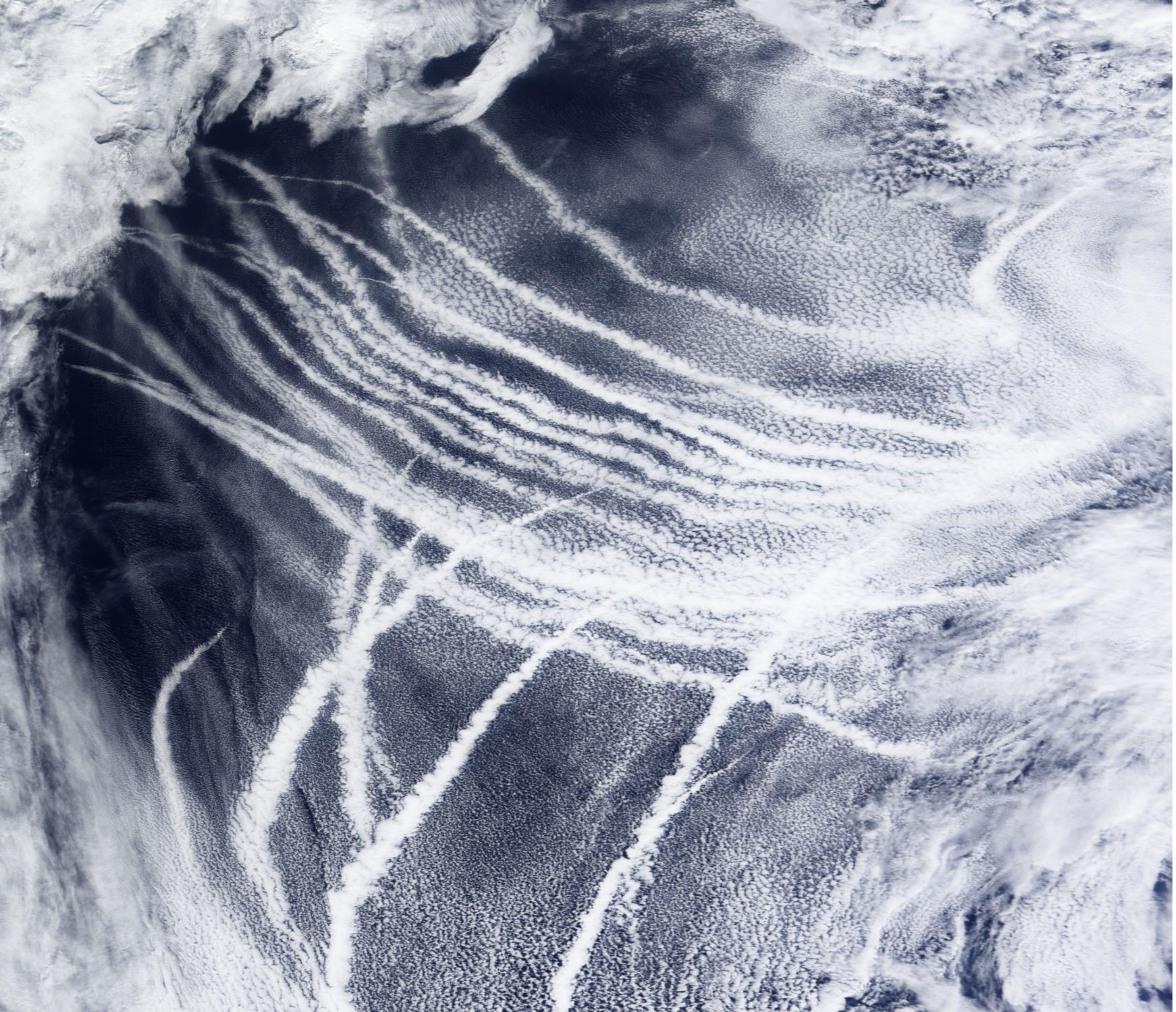


MARINECLOUD

— BRIGHTENING PROJECT —

Robert Wood,
Sarah Doherty,
Thomas Ackerman,
Peter Blossey, Matt Wyant

UNIVERSITY of WASHINGTON

Philip Rasch,
GK Kulkarni

Pacific Northwest NATIONAL LABORATORY

Sean Garner,
Kathryn Murphy,
Elif Karatay, Kalai Ramea

parc A Xerox Company

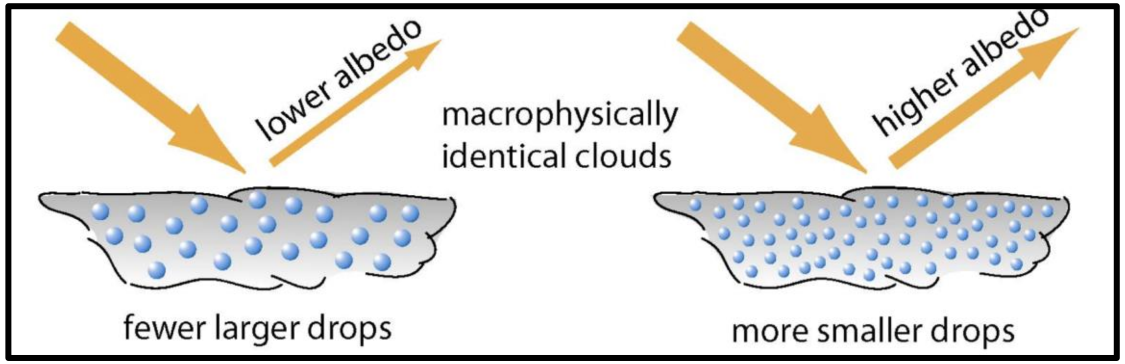
Kelly Wanser

SilverLining ENSURING A SAFE CLIMATE

Armand Neukermans,
Gary Cooper, Jack Foster,
Lee Galbraith, Robert Ormond,
Sudhanshu Jain

"Old SALTS"

Marine Cloud Brightening: Using sea-salt to brighten low clouds over the ocean

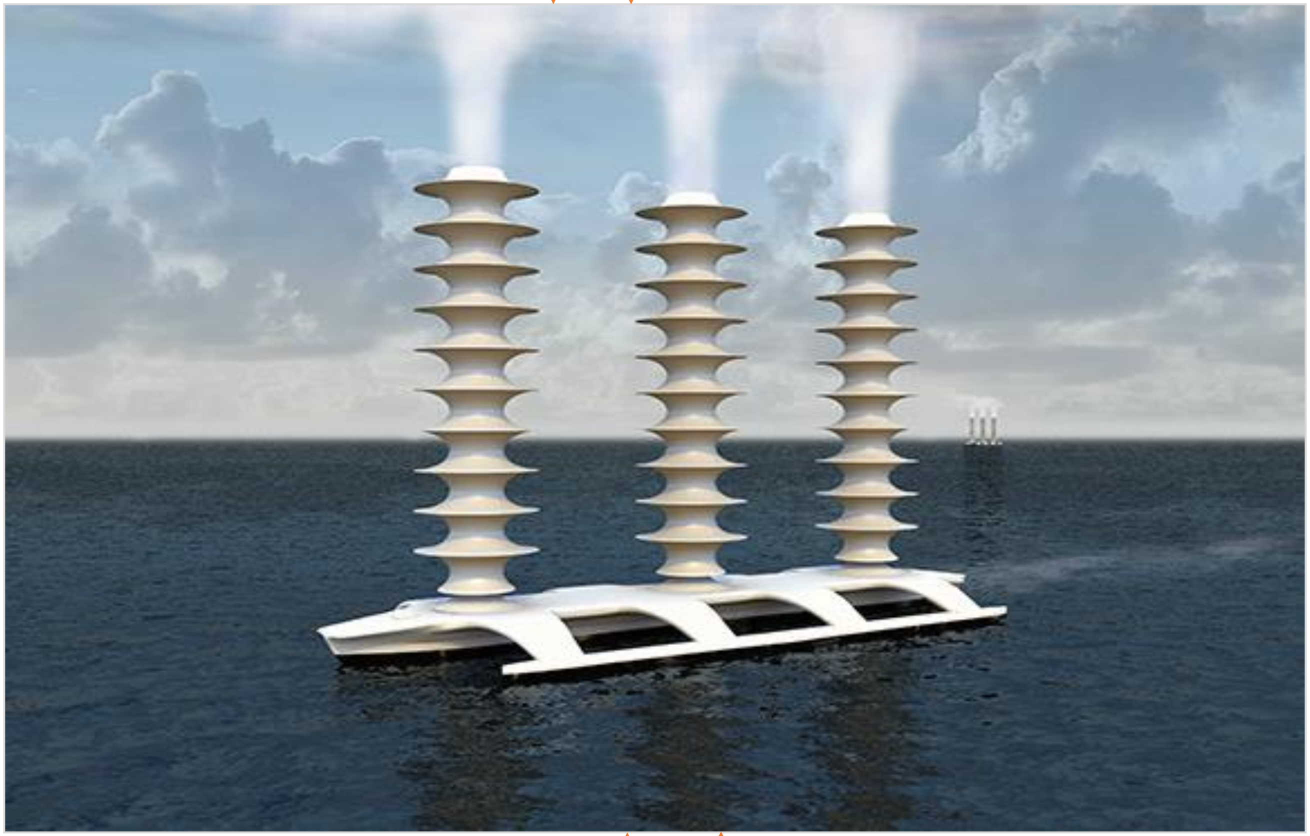


- Adding salt particles increases the number of cloud droplet nuclei
- Makes smaller, more numerous droplets
- Makes clouds more reflective
- (Might make clouds last longer)

Sea salt mist delivered from ships

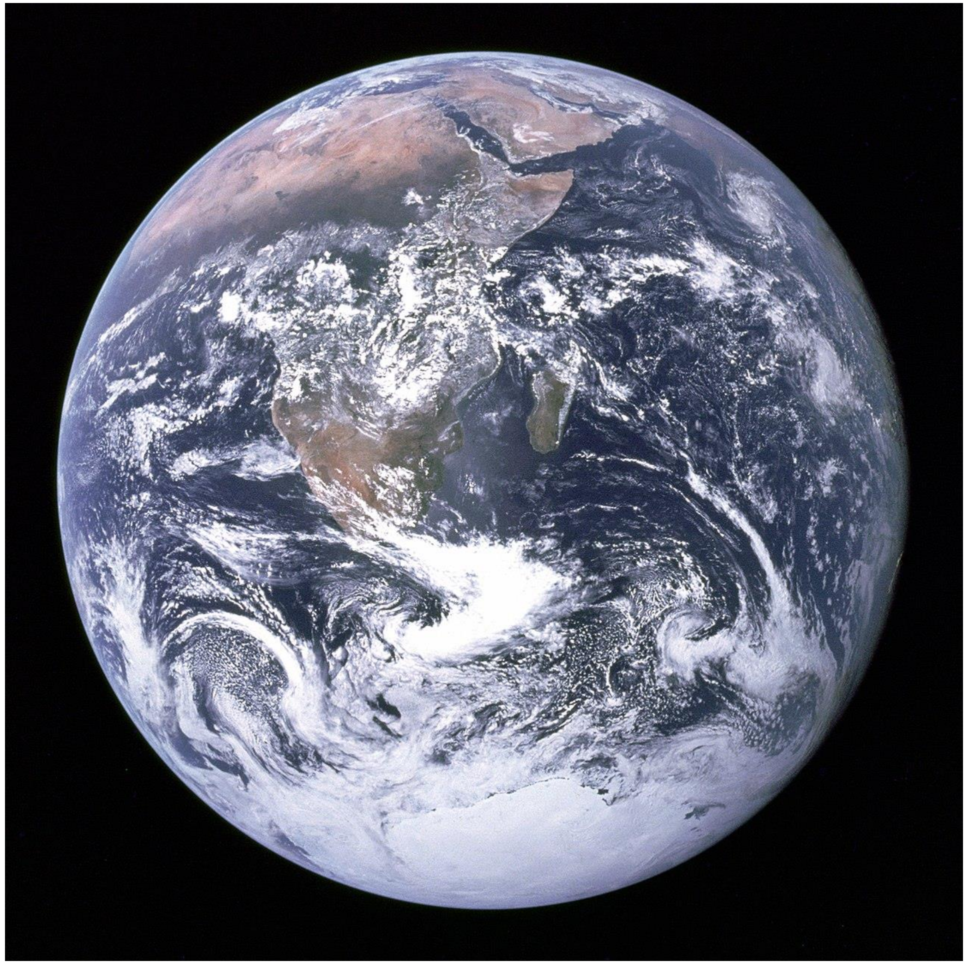
~30-100nm particles

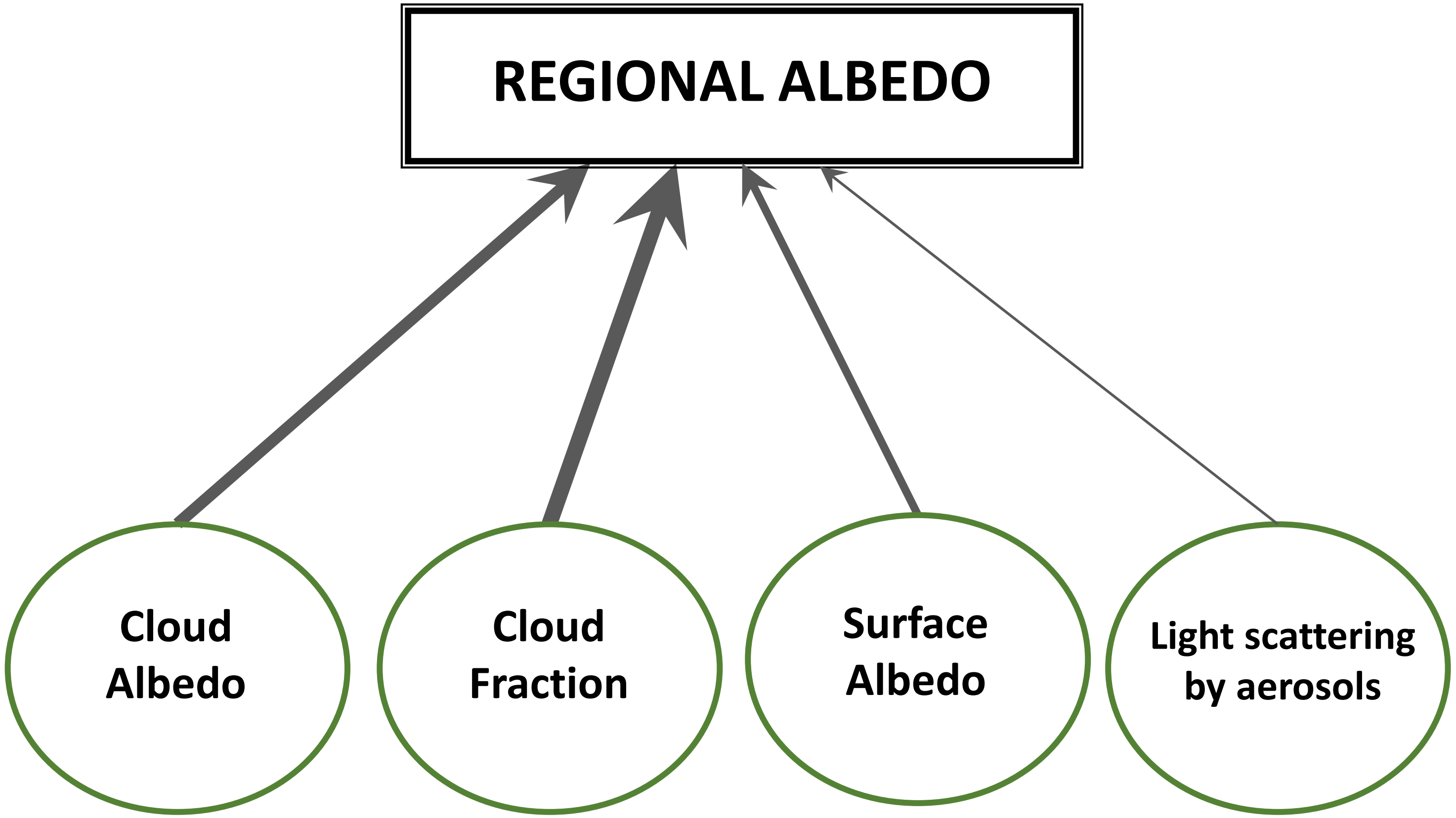
~10^{16} particles/second

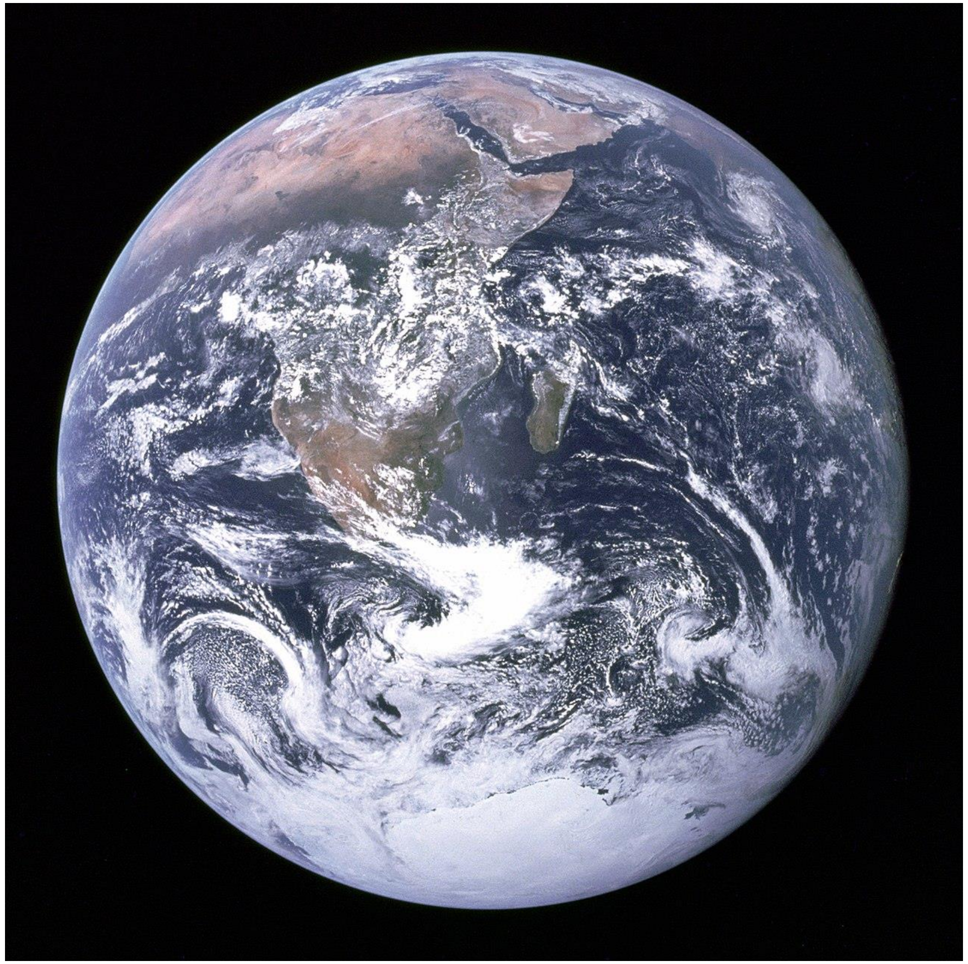


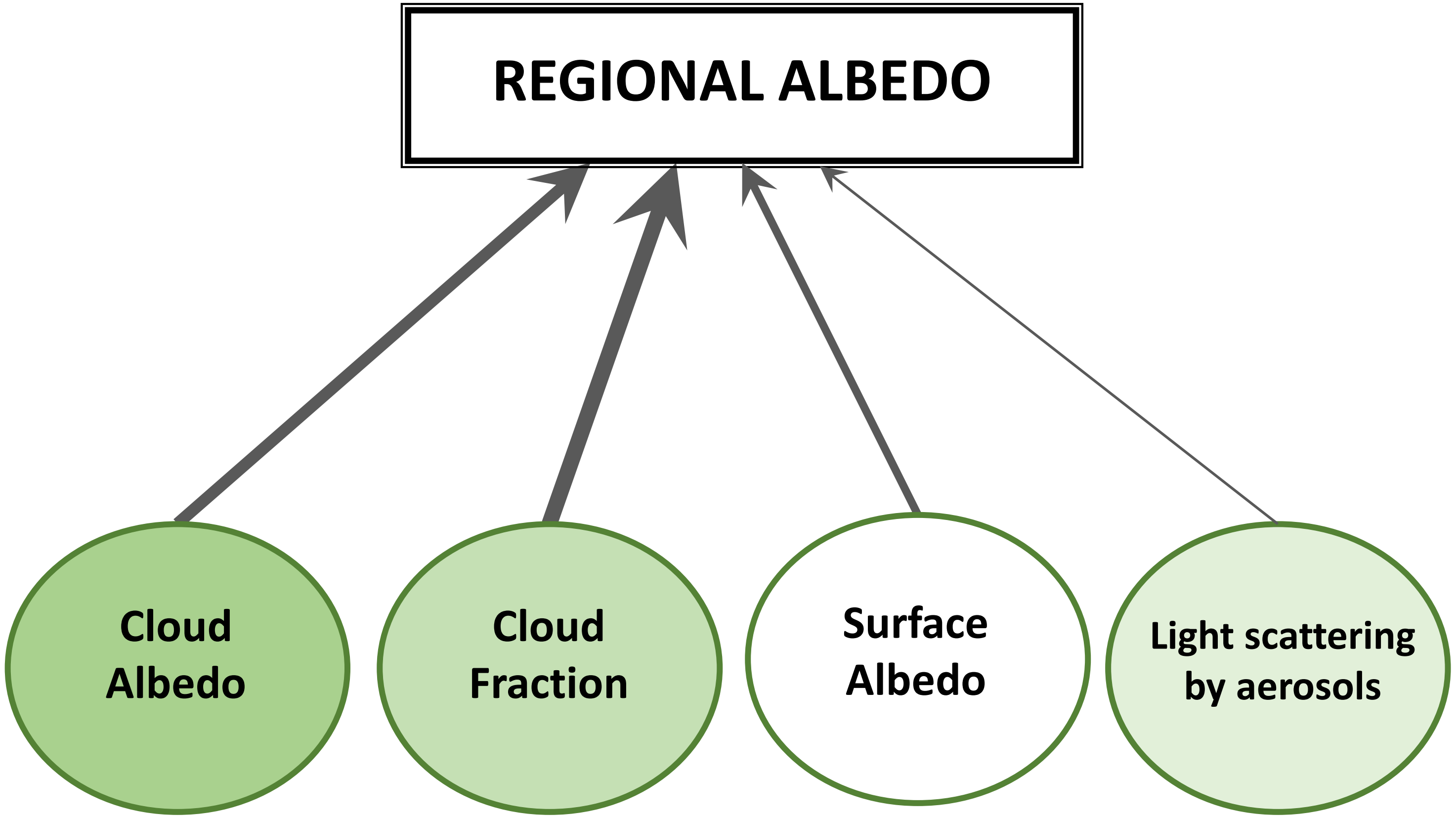
Ecologically benign material

Localized, temporary effects




REGIONAL ALBEDO
Cloud Albedo
Cloud Fraction
Surface Albedo
Light scattering by aerosols




REGIONAL ALBEDO
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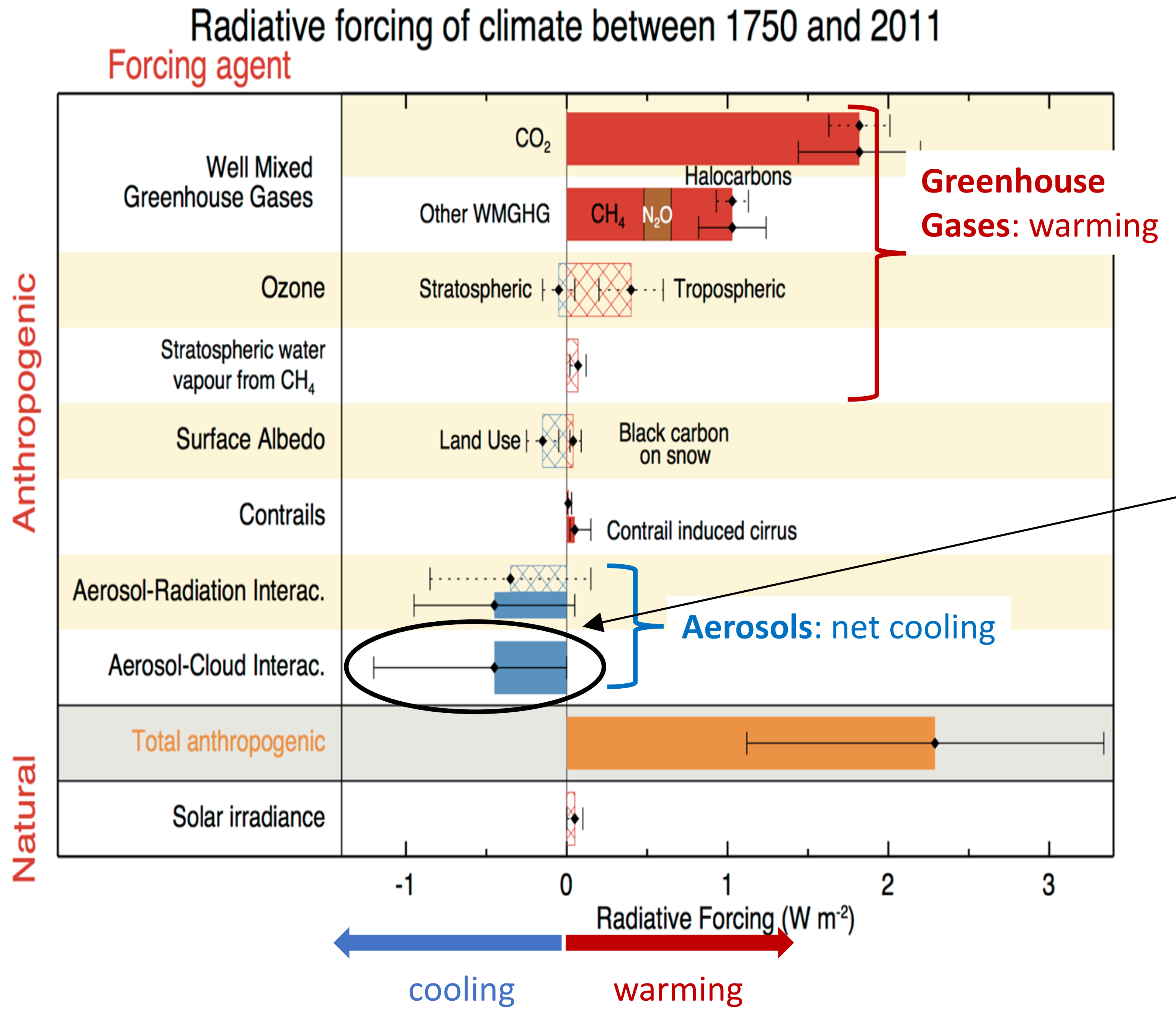


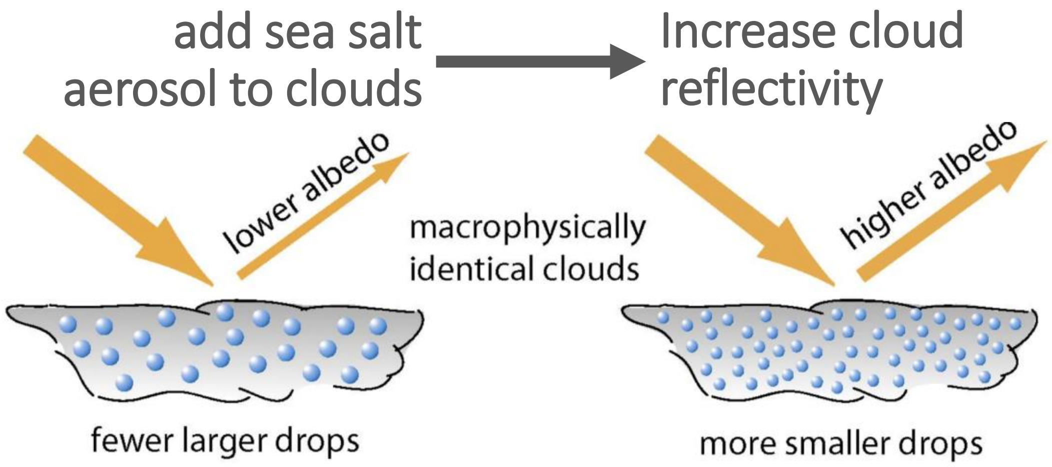
*"There is high confidence that **aerosols and their interactions with clouds** have offset a substantial portion of global mean forcing from well-mixed greenhouse gases. **They continue to contribute the largest uncertainty to the total [Radiative Forcing] estimate.** "*

IPCC 5th Assessment, 2013, Summary for Policymakers p. 13-14.

Anthropogenic radiative forcing, IPCC 2013

Cloud responses to aerosols

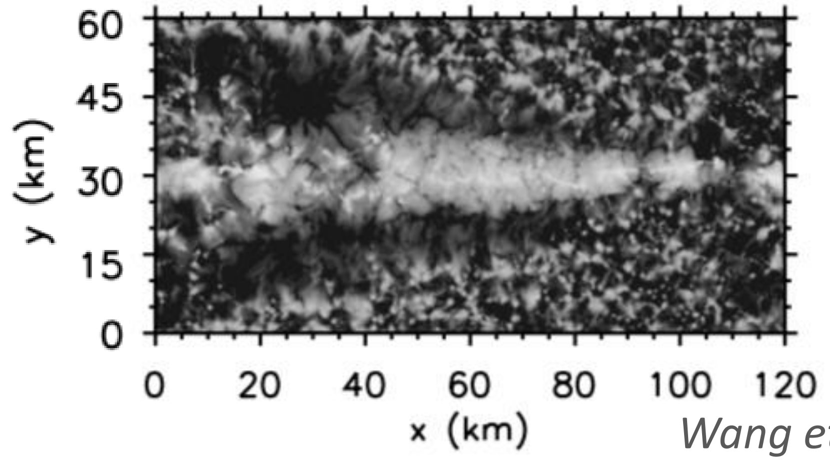
The idea behind MCB:



The reality:

- Cloud response depends strongly on:
  - Size & concentration of injected aerosol
  - Background aerosol conditions
    - Below & above cloud
  - Atmospheric conditions, e.g.:
    - Water availability below/above cloud
    - Cloud precipitating now/recently?

- Perturbed & adjacent clouds can be altered by dynamical responses to initial perturbation



Wang et al., 2011

MARINECLOUD

— BRIGHTENING PROJECT —

Aerosol technology	Aerosol-cloud interactions	Climate impacts	Human systems and social science
• Nozzle lab tests • Nozzle/spray system modeling • Spray system design • Boundary layer plume modeling • Open-air testing	• Boundary layer modeling • Ship-track/MCB modeling • Field experiments • Spray system optimization	• Regional forcing/effects • Use for targeted applications • MCB global forcing estimate • Improve estimates of forcing via aerosol-cloud interactions	• Research design • Operational studies • Social sciences

Challenge: Generate aerosol of the right size & quantity

N'_a : # particles sec^{-1} added to BL/cloud by a single spray system

$$N'_a = \frac{N_a A H}{\tau}$$

N_a: desired increase in particle concentration (e.g. 300-400 cm^{-3})

H: BL height (~1km)

τ: lifetime of the aerosol in BL (~3 days)

A: area covered by a single spray system (2000 km^2)

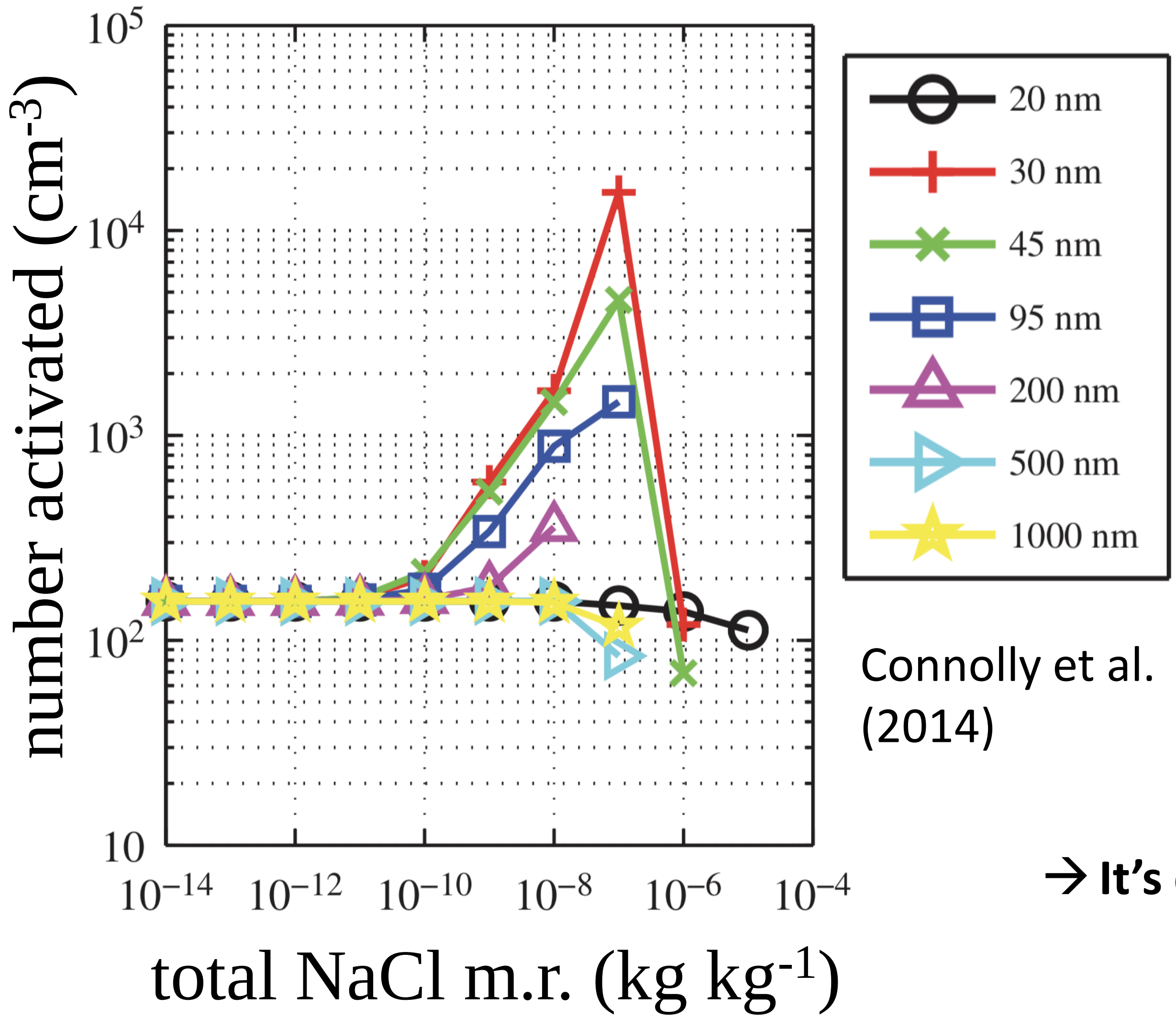
→ N'_a : 2-3×10^{16} particles/sec

Single nozzle: ~10^{12} particles/sec

2-3,000 nozzles per spray system

→ **Aerosol of choice: sea salt**

Challenge: Generate aerosol of the right <u>size</u> & <u>quantity</u>



Connolly et al. (2014)

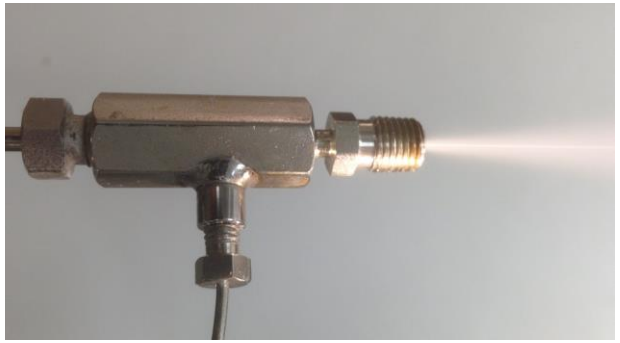
The Goldilocks problem…

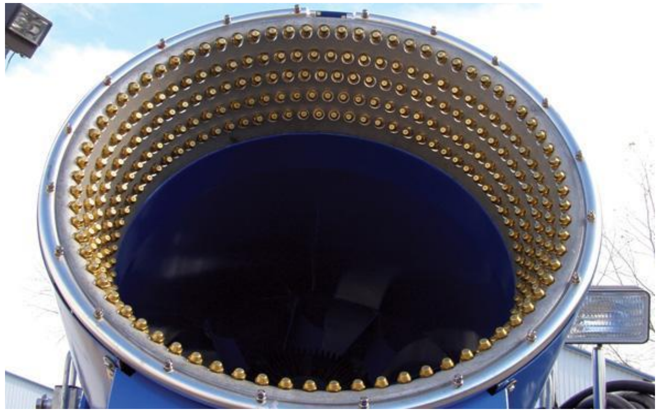
- Aerosol too small: doesn't activate cloud droplets
- Aerosol too large: the mass of sea salt – and therefore sea water – needed is too energy-inefficient
- Aerosol much too large: can actually lead to reduced cloud LWP by increasing precipitation rate
- "Just right": 30nm< diameter < 100nm

→ **It's difficult to mechanically produce aerosol this small!**

MCB Aerosol Technology development:
A new Instrument for Cloud Physics Research

CFD* modeling ↔ spray system design ↔ lab tests



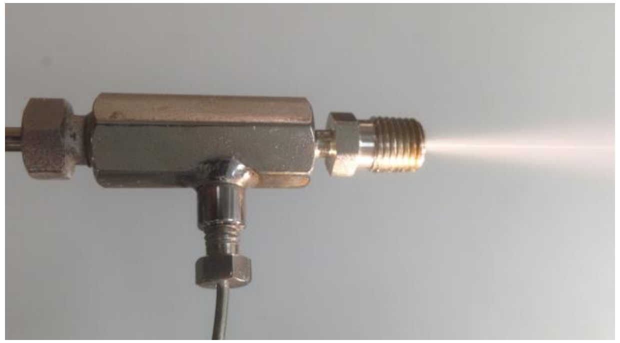


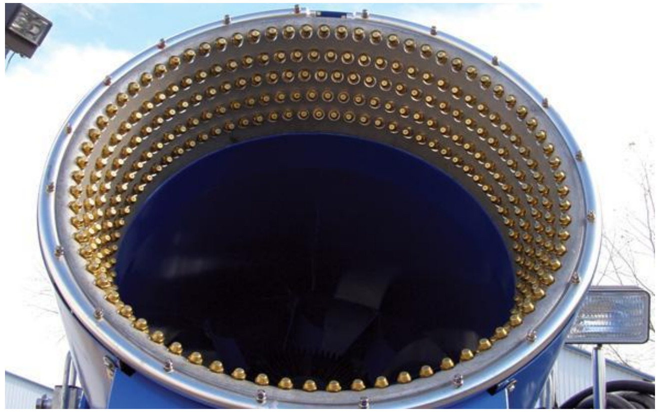
Research-grade
spray system

** CFD= Computational Fluid Dynamics*

MCB Aerosol Technology development:
A new Instrument for Cloud Physics Research

CFD* modeling ↔ spray system design ↔ lab tests ↔ LES modeling ↔ open-air tests**





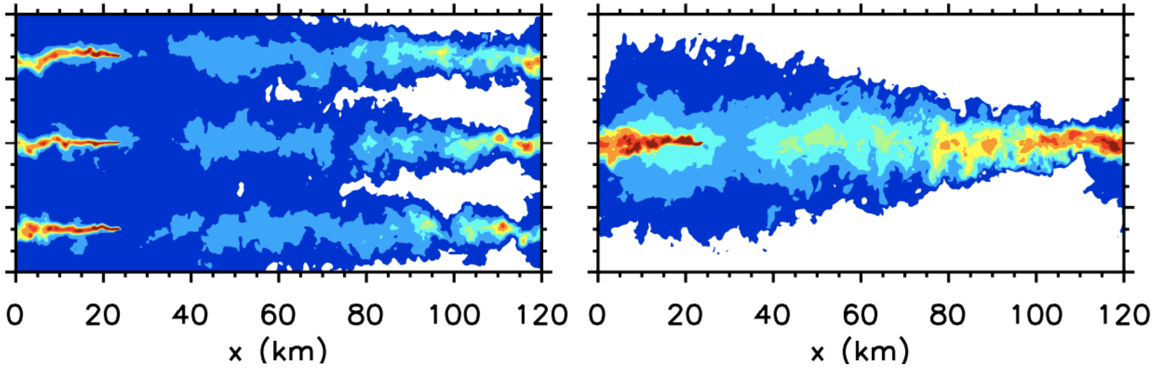
Research-grade
spray system

** CFD= Computational Fluid Dynamics*
*** LES = Large Eddy Simulation*

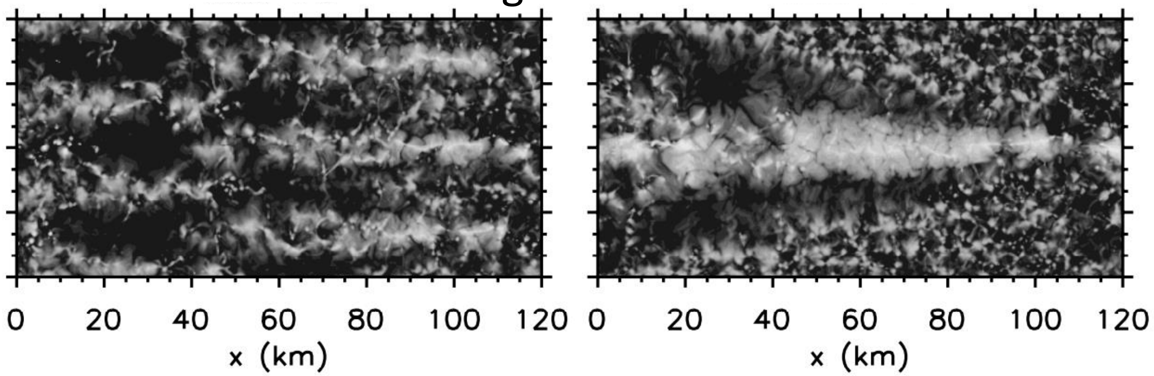
Aerosol-Cloud Interaction Studies

Cloud–scale, high resolution modeling studies

Injected aerosol plumes



Resulting cloud fields

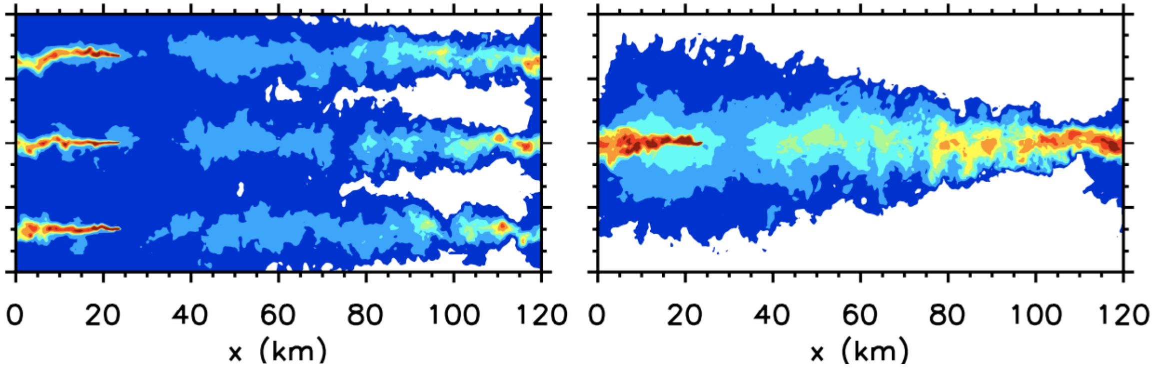


Wang et al., 2011

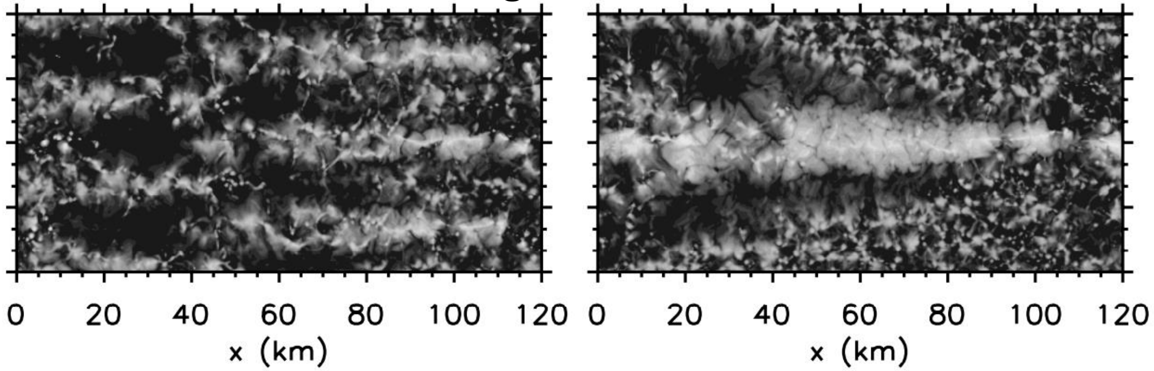
Aerosol-Cloud Interaction Studies

Cloud–scale, high resolution modeling studies

Injected aerosol plumes



Resulting cloud fields

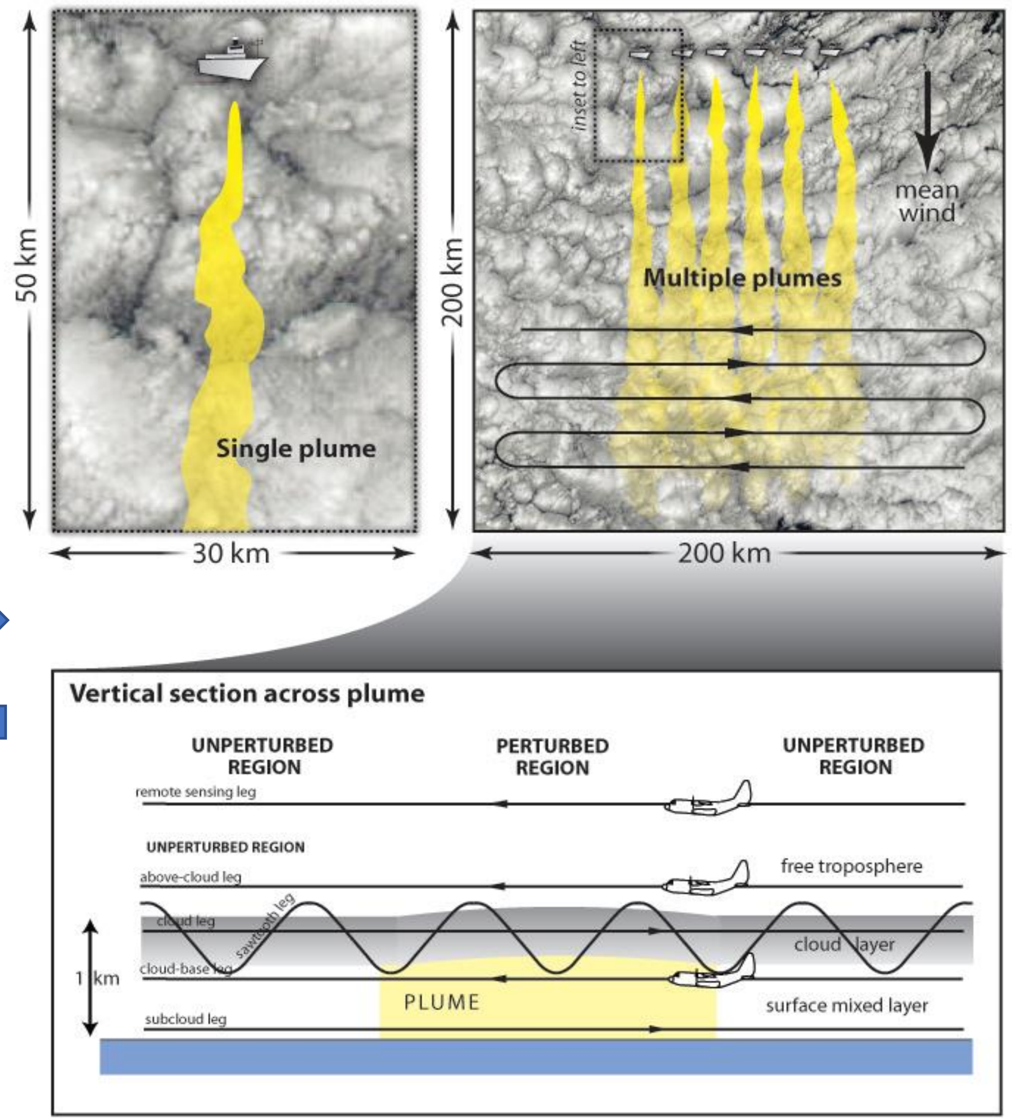


Wang et al., 2011

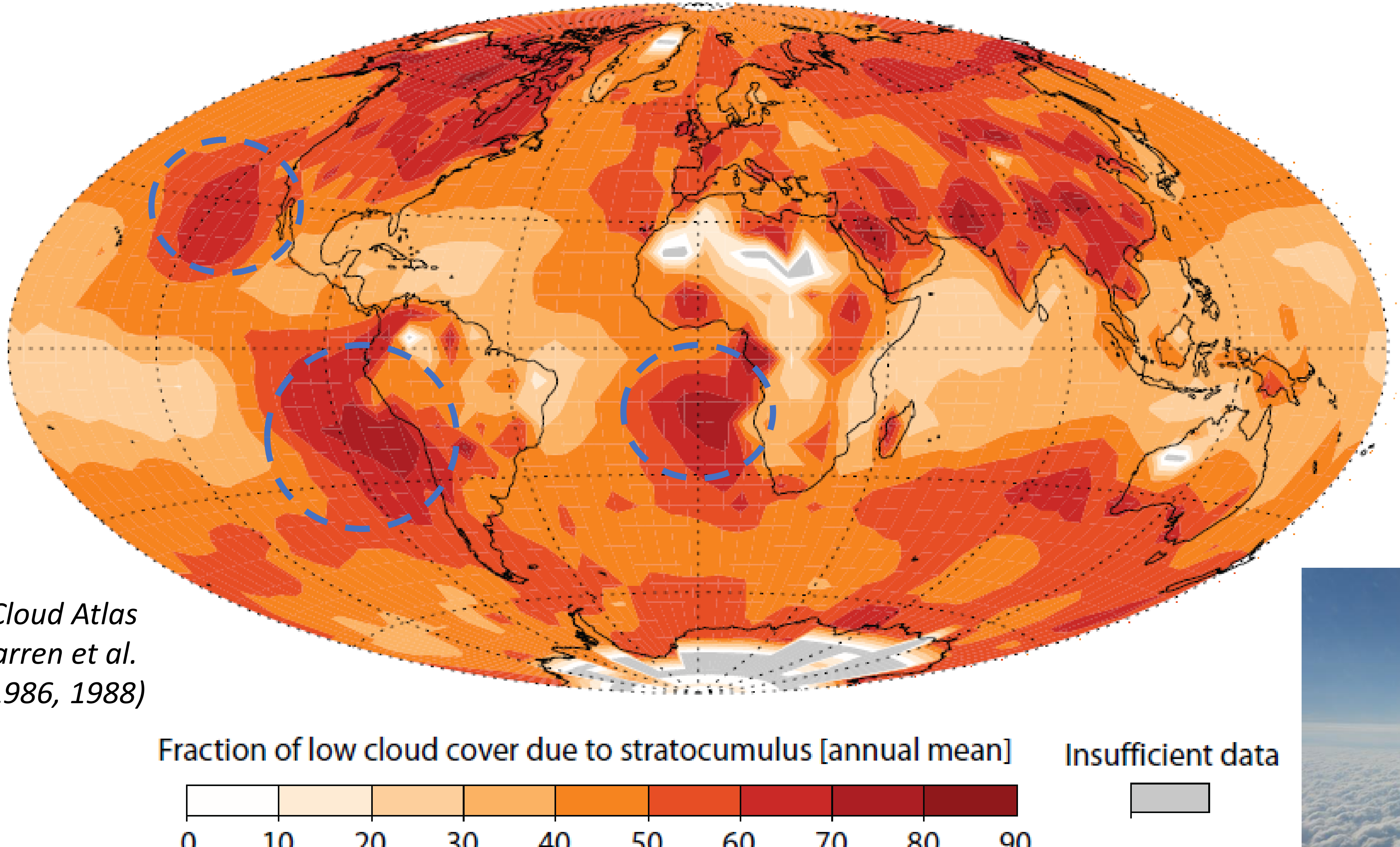
Parameterization development

Single-plume field study

Multi-plume field study



Stratocumulus cloud cover



Cloud Atlas
Warren et al.
(1986, 1988)

Oceans

Sc coverage: 22%

Cu coverage: 13%

Eastman et al. (2011)

Field studies of aerosol-cloud interactions for MCB:

Will be built on extensive experience in studies of aerosol-cloud interactions in “non-controlled” studies

MCB Climate Impacts Assessment

- Implement improved parameterizations in regional & global-scale models
- Utilize "natural experiments" (ship tracks, volcanic plumes) to assess potential efficacy of MCB for increasing Earth reflectivity
- Machine learning for large-scale data analytics, accelerated climate model simulations, and uncertainty quantification
- Assess:
  - Potential for MCB to reduce climate warming
  - Impacts, e.g.:
    - regional temperature, precipitation impacts
    - ocean surface temperature & biological impacts
  - Potential for localized MCB implementation for targeted uses, e.g.:
    - Coral reef protection
    - Reducing hurricane intensity

Learning from MCB research → reducing uncertainty in forcing via aerosol-cloud interactions in present-day