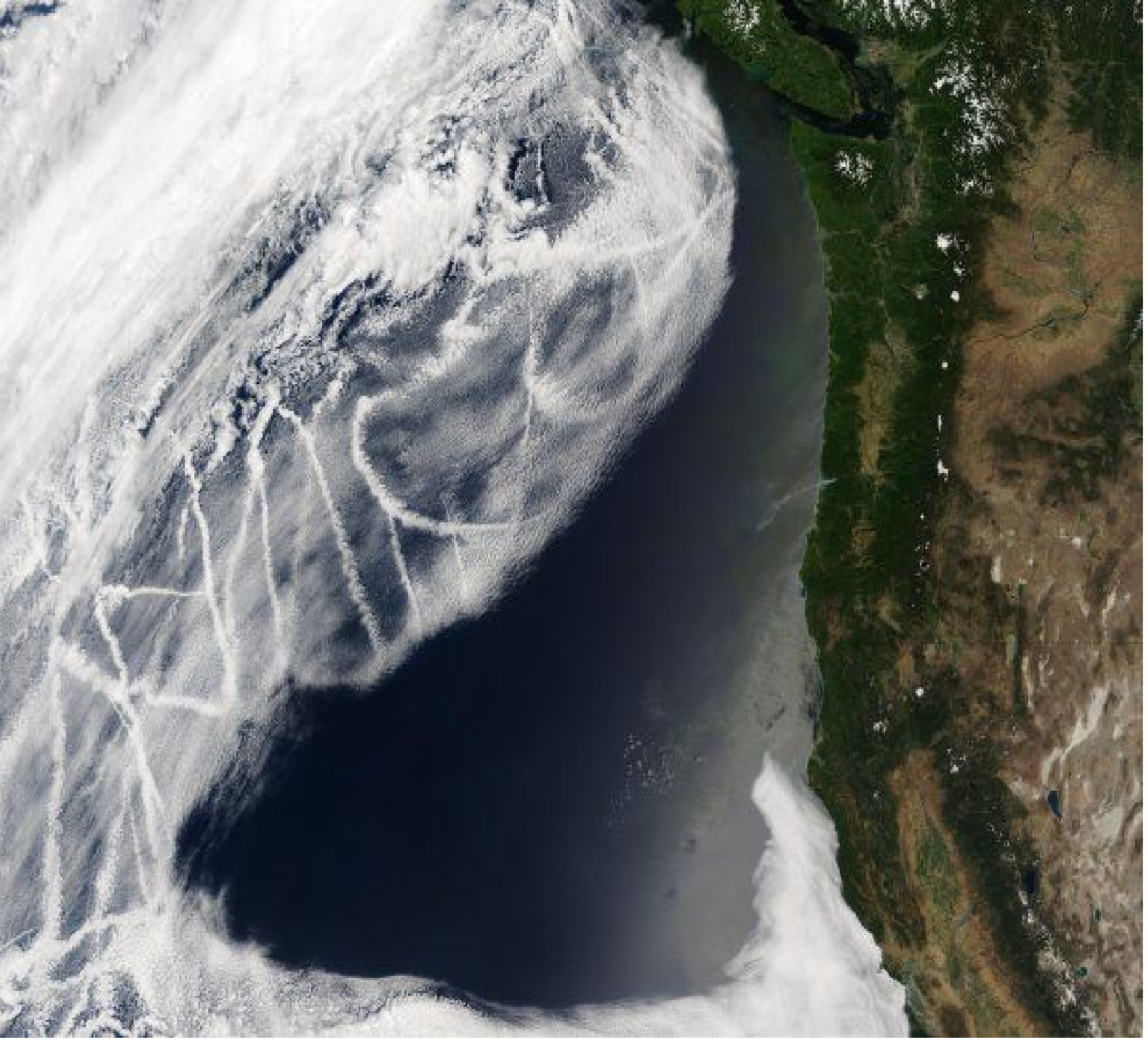


Marine Cloud Brightening: Science, Feasibility and a Plan for Research

Robert Wood

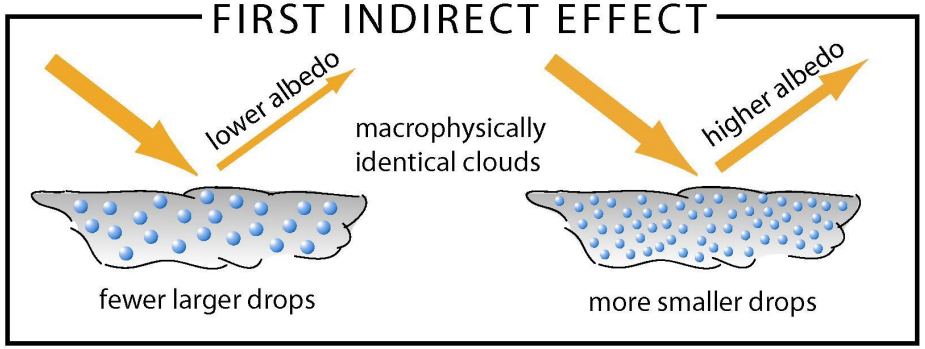
Department of Atmospheric Sciences, University of Washington, Seattle

Contributors

- **Thomas Ackerman**, Director, Joint Institute for Atmosphere and Ocean, Univ. Washington
- **Philip Rasch**, Chief Climate Scientist, PNNL
- **Anna Possner**, Postdoc, Carnegie Science, Stanford
- **Armand Neukermans**, Chief Engineer, MCB Project
- **Kelly Wanser,** Principal Director, MCB Project

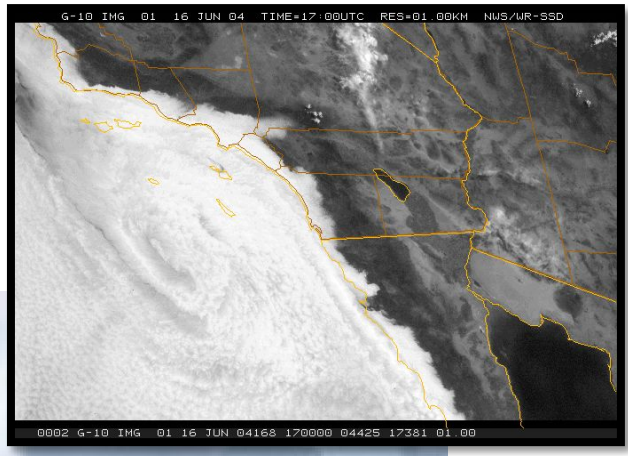
MARINECLOUD
— BRIGHTENING PROJECT —

Marine Cloud Brightening proposes using sea-salt mist to brighten low clouds over the ocean



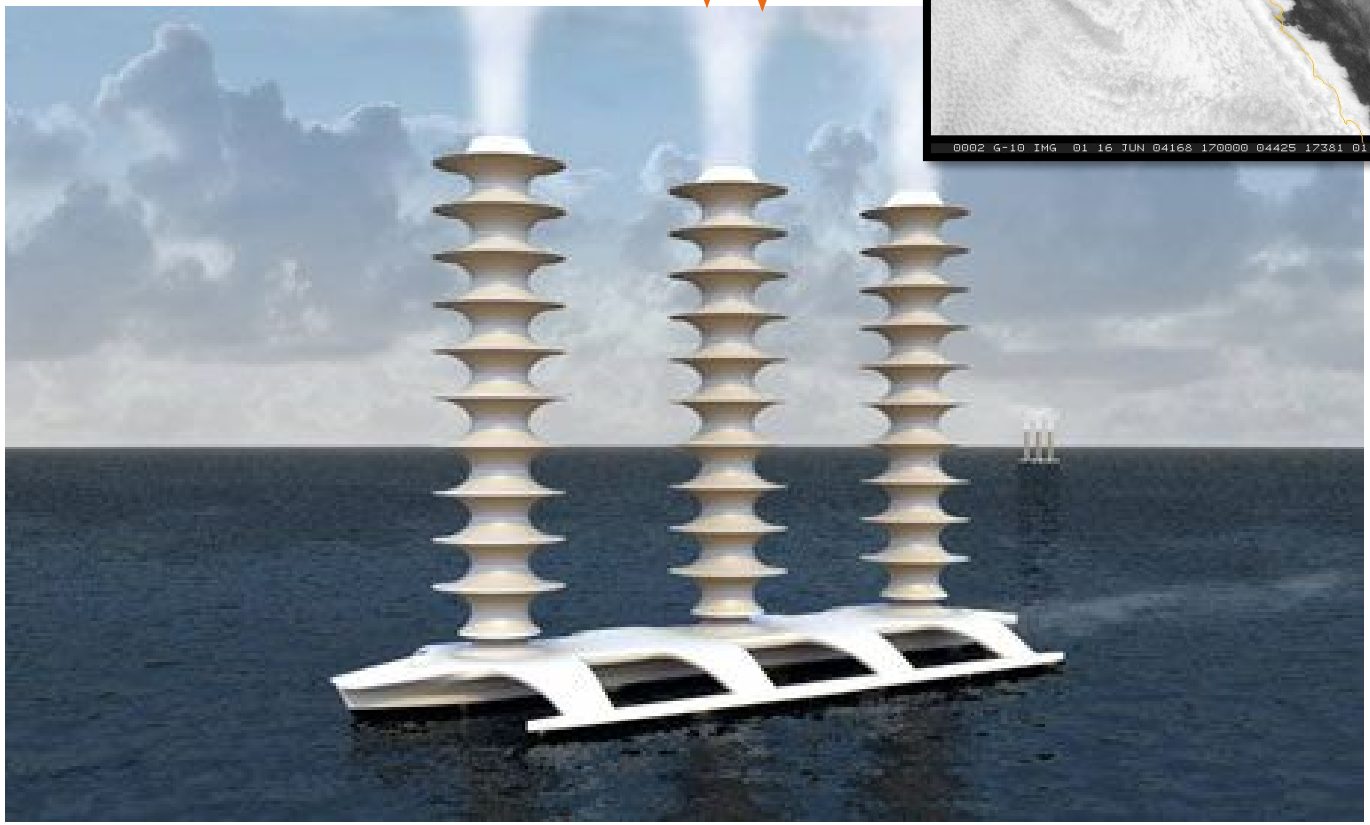
- Adding salt particles increases cloud droplet nuclei number
- Makes smaller, more numerous droplets
- Makes cloud more reflective and more sustained

Identify susceptible marine clouds



100 nanometer particles

10^{15} particles/second



Ecologically benign material

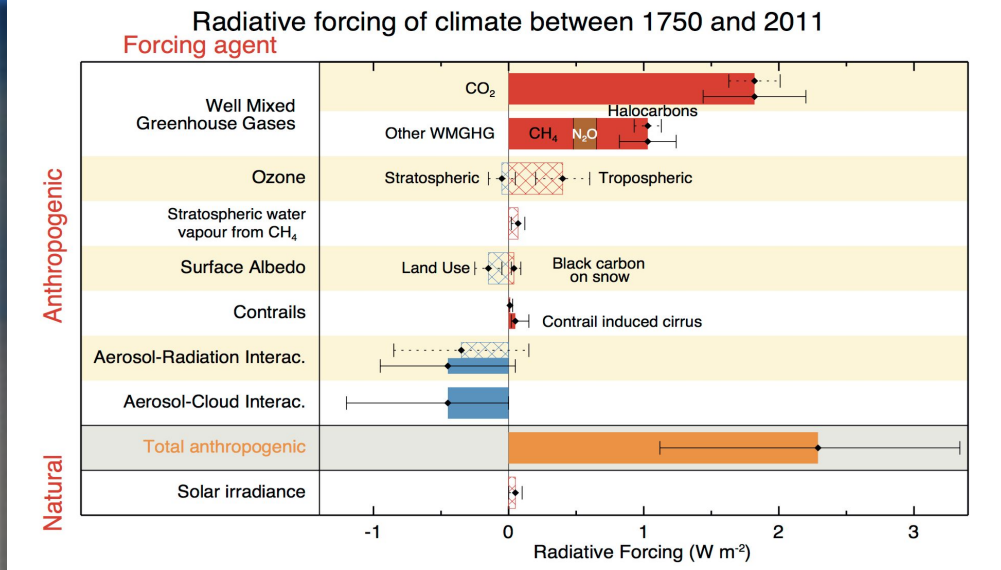
Localized, temporary effects

Infuse with mist delivered from ships

Marine cloud brightening, John Latham, et al Philosophical Transactions A, 2012.DOI: 10.1098/rsta.2012.0086

Today, anthropogenic aerosol particles mix with clouds creating a cooling effect, estimated at between 0.5°C and 1.5°C

- Most Particles cool by
  - Reflecting sunlight directly
  - Affect clouds in a way that increases the amount of sunlight they reflect ("cloud-aerosol effect")
- Some particles (soot) warm
- *The net effect is a cooling*



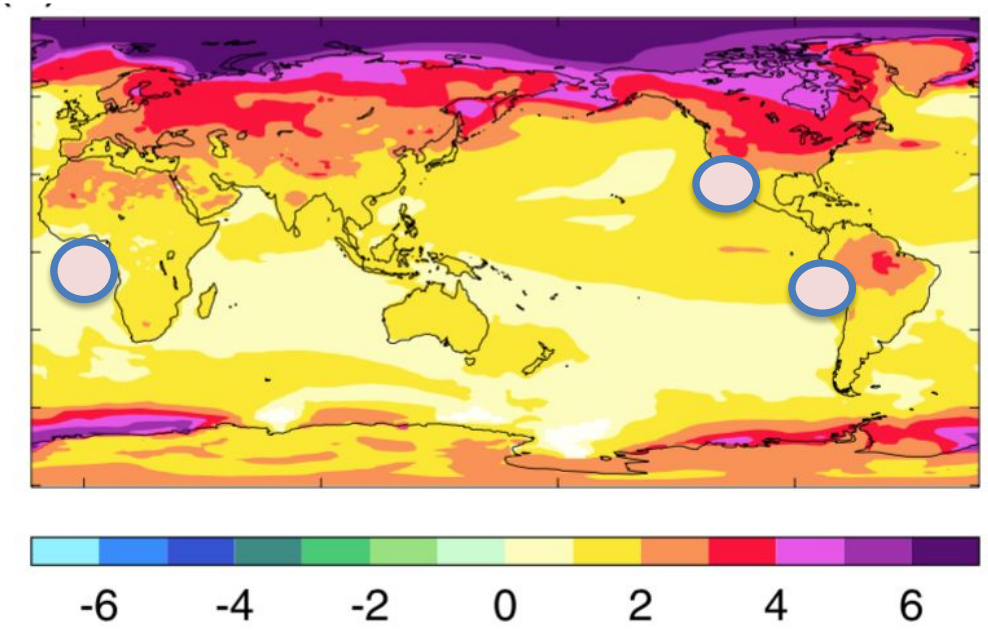
Anthropogenic radiative forcing, IPCC 2013

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*

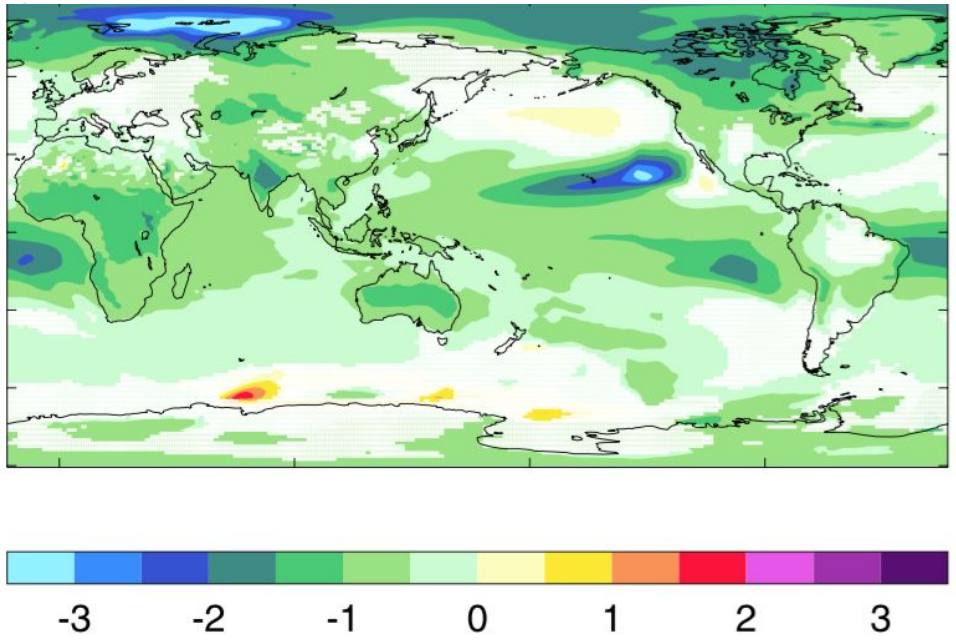
Applied to 10-50% of marine clouds, it might be possible to offset a significant fraction of CO_2 forcing globally with MCB

Jones et al. (2009)

Warming from CO2 increases



Cooling from MCB covering 3% of Earth's Surface Area

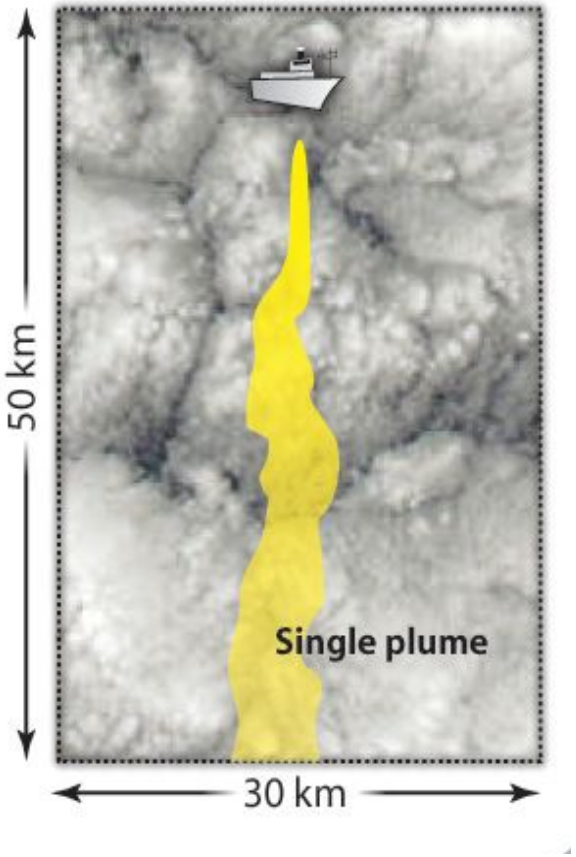


Jones et al. (2009), Stjern et al. (2017), inter alia.

Dual Purpose Research program aimed at major gap in climate science

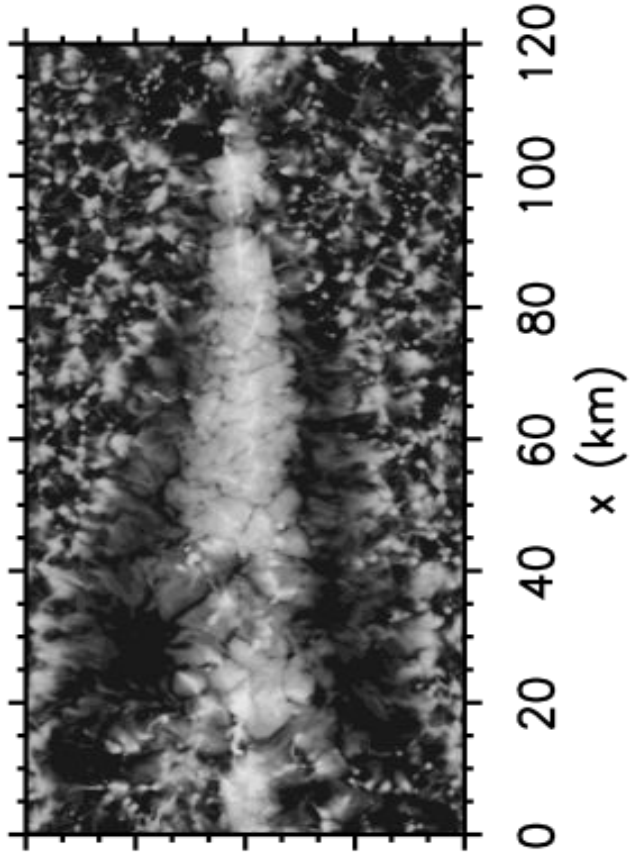
MCB Field Experiments

- Provide scientific insight into cloud-aerosol interaction and test MCB effect on cloud microphysics
- Controlled, well-defined aerosol injected into marine boundary layer



Cloud-aerosol models

- Simulate plume releases at multiple scales
- Experiments test against model findings
- Improve cloud-aerosol representation in climate models
- Critical advances in climate science

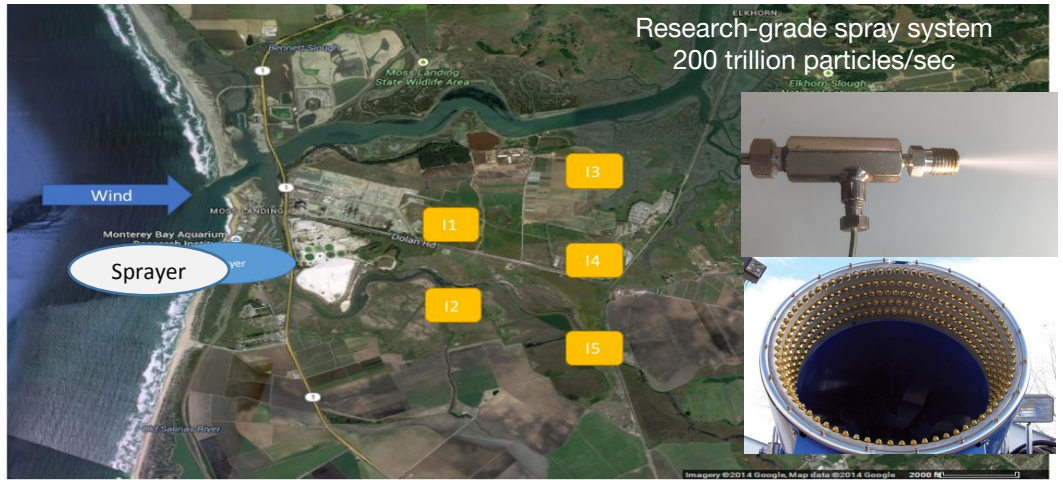


Wood, R., and T. P. Ackerman (2013): *Climatic Change*, 121, DOI 10.1007/s10584-013-0932-z, 2013.

Wang, H., Rasch, P. J., and Feingold, G. *Atmos. Chem. Phys.*, 11, 4237-4249, doi.org/10.5194/acp-11-4237-2011, 2011.

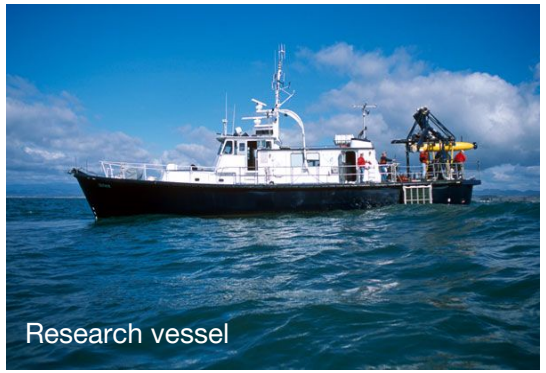
Marine Cloud Brightening Experimental Research Program

1. Land-based testing in a coastal environment

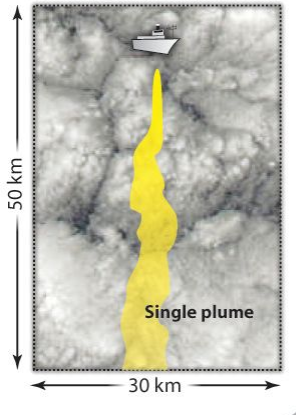


Source: Tom Ackerman, University of Washington

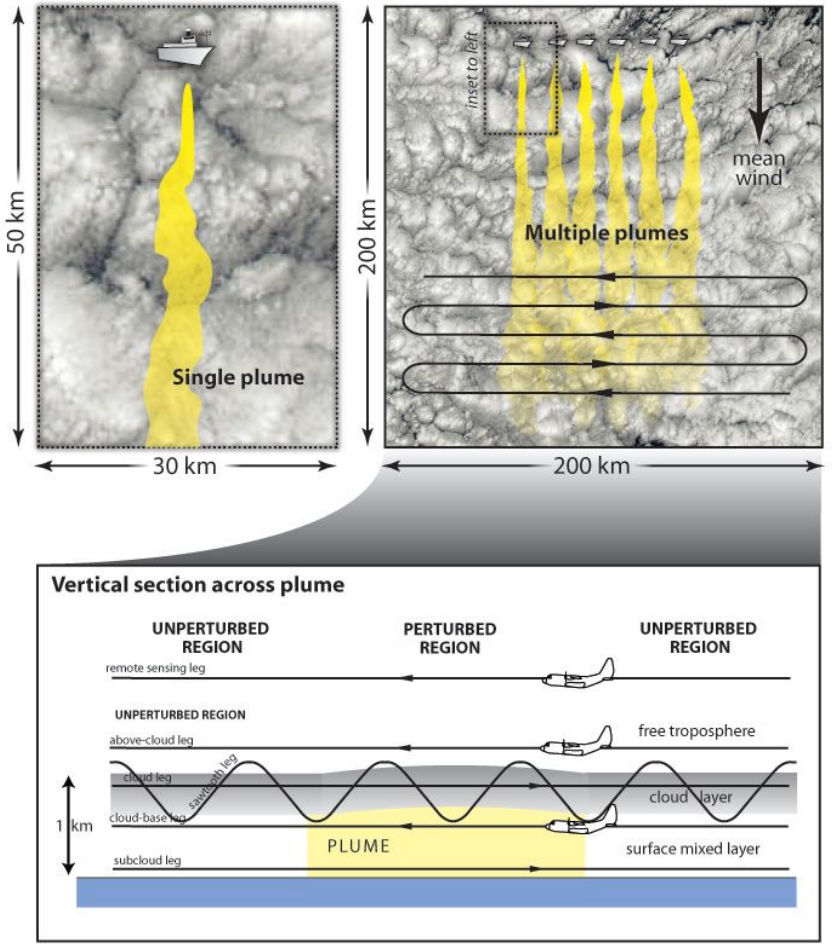
2. Cloud-aerosol interaction single-plume experiments



Possible autonomous observation platforms



3. Limited Area Field Experiment

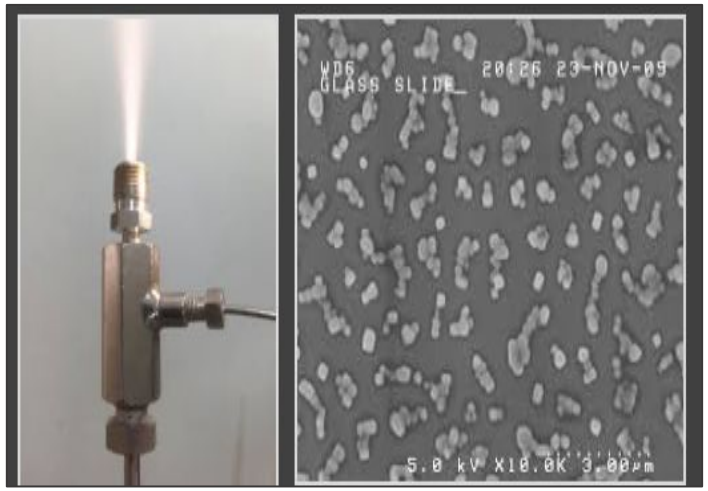


Design based on prior observational aircraft/ship studies

Wood, R., and T. P. Ackerman (2013): Defining success and limits of field experiments to test geoengineering by marine cloud brightening. R. Wood and T. P. Ackerman. *Climatic Change*, 121, DOI 10.1007/s10584-013-0932-z, 2013.

Substantial technology development is required

Particle generation
Ecologically benign, nanoscale



- 100 nanometer particles
- Narrow size distribution
- Benign (but corrosive) material (salt)
- Method: Effervescent spray, Taylor-cones

Delivery systems
Cloud-scale, energy-efficient

- 10^{15} particles/second
- 100-200 bar pressure, 200-300kW power
- Research: commercial snow-makers
- Deployment: power-efficient, tunable

Observation & analytics
Multi-platform, analysis-intensive

- Surface LIDAR/RADAR
- Aircraft/drone
- Satellite
- Post-measurement analytics
- Pre/post modeling

Hard problem: Silicon Valley aerosol experts took 6 years to solve

MCB may have local or regional applications to reduce climate impacts

Change precipitation patterns to increase moisture

(Photo courtesy of Christopher Michel)

Reduce hurricane strength

Prevent coral bleaching

Weakening of hurricanes via marine cloud brightening (MCB), Latham, et al, Atmospheric Science Letters 23 August 2012

The Effects of Marine Cloud Brightening on Seasonal Polar Temperatures and the Meridional Heat Flux, Parkes et al. ISRN Geophysics 2012

Summary

- Introducing additional salt particles into marine low clouds can increase their ability to reflect solar radiation
- Models suggest offsetting significant fraction of greenhouse gas warming is feasible, but representing aerosol-cloud interactions in climate models is a major challenge
- Dual purpose research program will provide important scientific insights into a major problem in climate research, and new constraints for models.

Additional slides

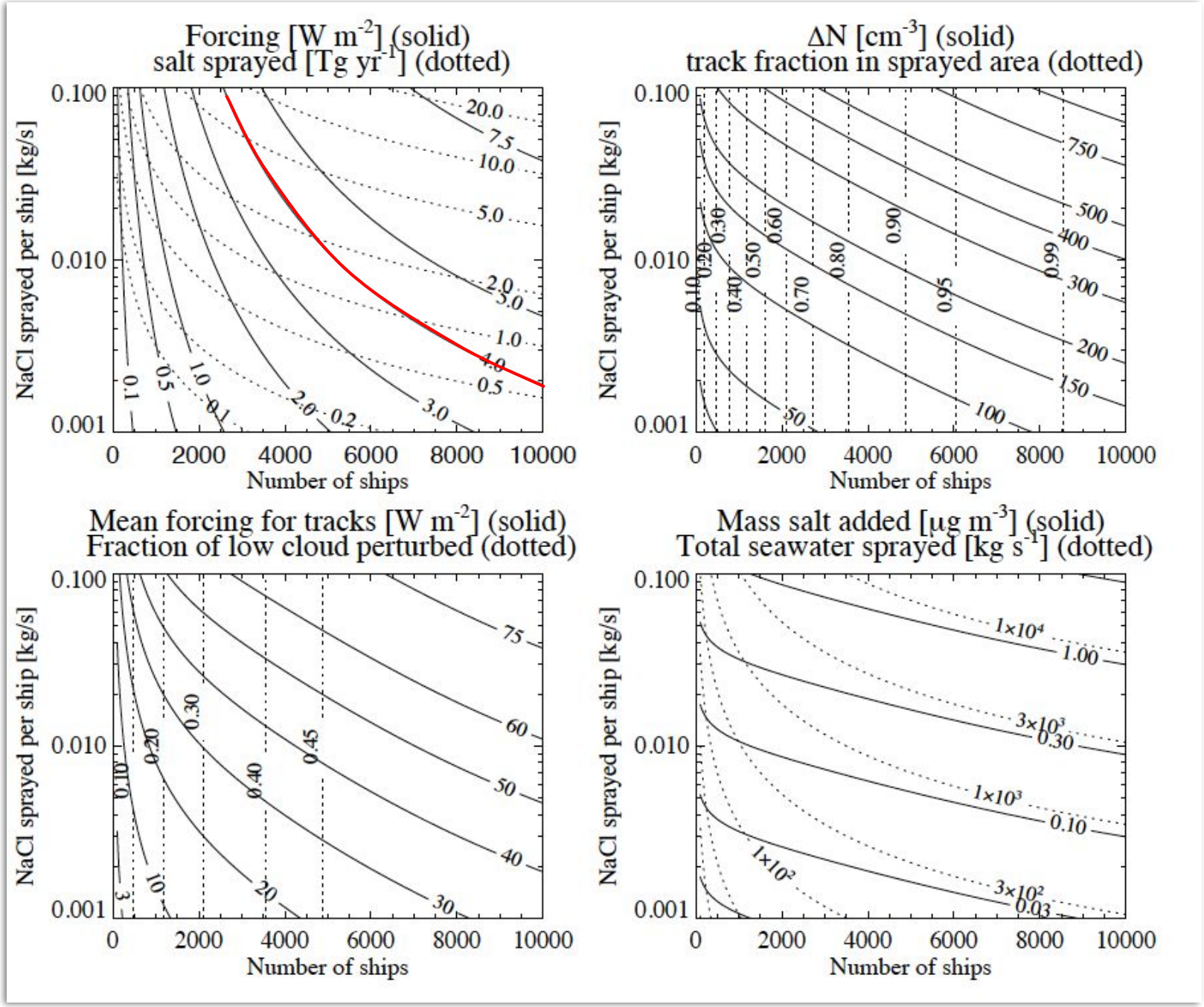
Marine Cloud Brightening Experimental Research Plan

Stage 1: Sprayer tests			Stage 2: Cloud-aerosol interaction tests: single plume			Stage 3: Limited Area Field Experiment (LAFE)		
Test [*location*]	**Duration**	**Key Equipment [*Analysis timescale*]**	**Test [*location, season*]**	**Duration**	**Key Equipment [*Analysis timescale*]**	**Test [*location, season*]**	**Duration**	**Key Equipment [*Analysis timescale*]**
Indoor dispersion test [*Ames Hangar*]	1-3 mo (repeats as needed)	Particle size spectrometers [*weeks*]	Coastal cloud impacts [*California coastal site, Spring/Summer*]	1-2 mo	Ground sites, Aircraft, Tethered Balloon [*3-6 mo*]	Cloud albedo responses to merged plume from 5-10 sprayers over 100x100 km region [*NE Pacific ~500-1000 km offshore, Spring/Summer*]	1-2 mo	Ship-ready sprayers, multiple deployment platforms, long range research aircraft (3), satellites, research vessel [1-2 yr]
Outdoor dispersion test [*Chico?*]	1 mo	Scanning lidar [*month*]	Single shiptrack [*~100 km offshore, Spring/Summer*]	2-3 mo	Ship-ready sprayer, short range research aircraft (1-3), satellites, research vessel? [*3-6 mo*]			
Coastal Dispersion [*Moss Landing?*]	1-2 mo	Aircraft instrumented with particle size spectrometers [*2-4 months*]						
1-2 years, $3m			2-3 years, $10m+			3-5 years, $30m+		

Source: Kelly Wanser, Marine Cloud Brightening Project

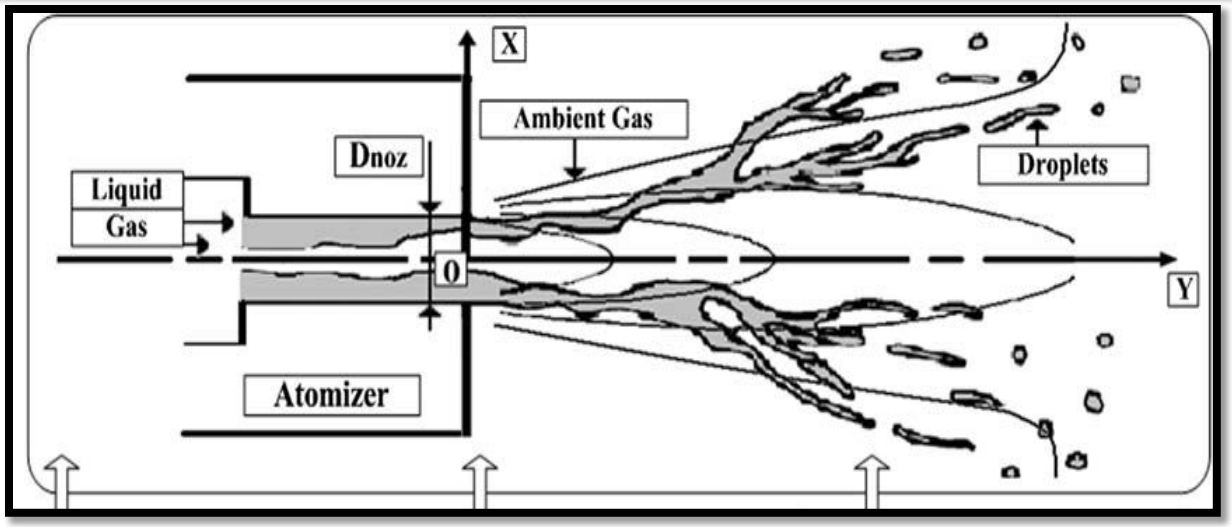
Simple model calculations of global forcing from Twomey effect

- Assume 50% of marine low clouds area is subject to spraying
- Estimate mass of salt sprayed and forcing as a function of number of ships spraying and mass sprayed per ship

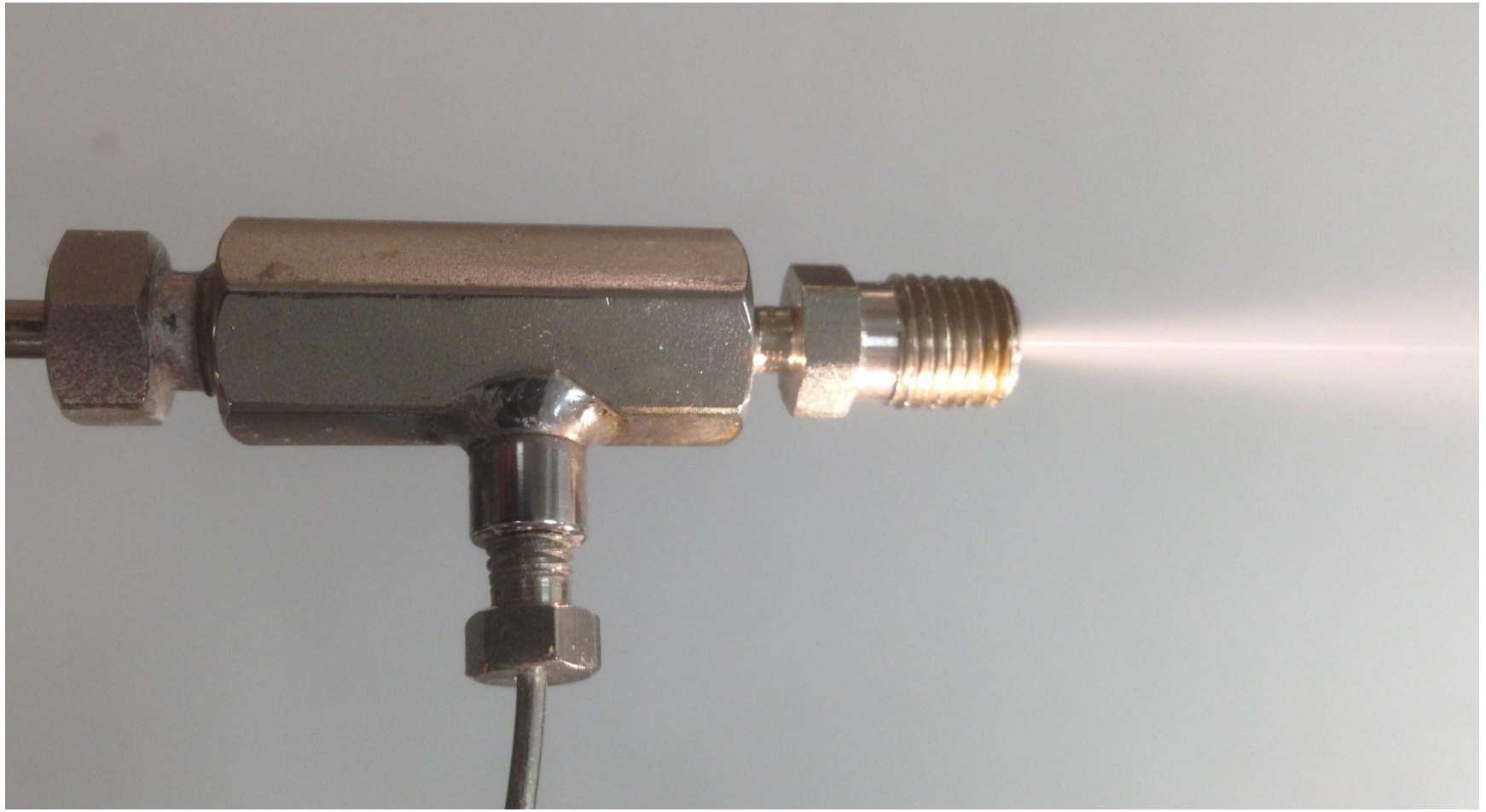


Aerosol technology: Exploding Annular Flow Mode 6-years to develop

Figure 4 Schematic display of primary atomization of the effervescent jet. (a) Inner flow [24]; (b) photo of primary breakup [40]; (c) assumption of modeling.



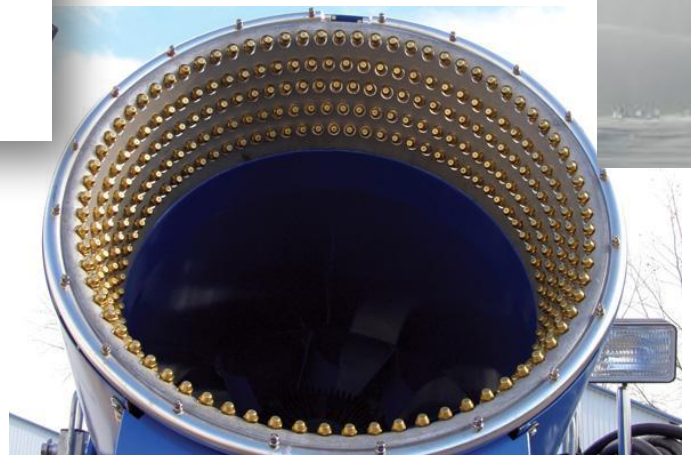
Lab spray nozzle: 1 trillion particles/sec



Research-grade spray system: still to be built

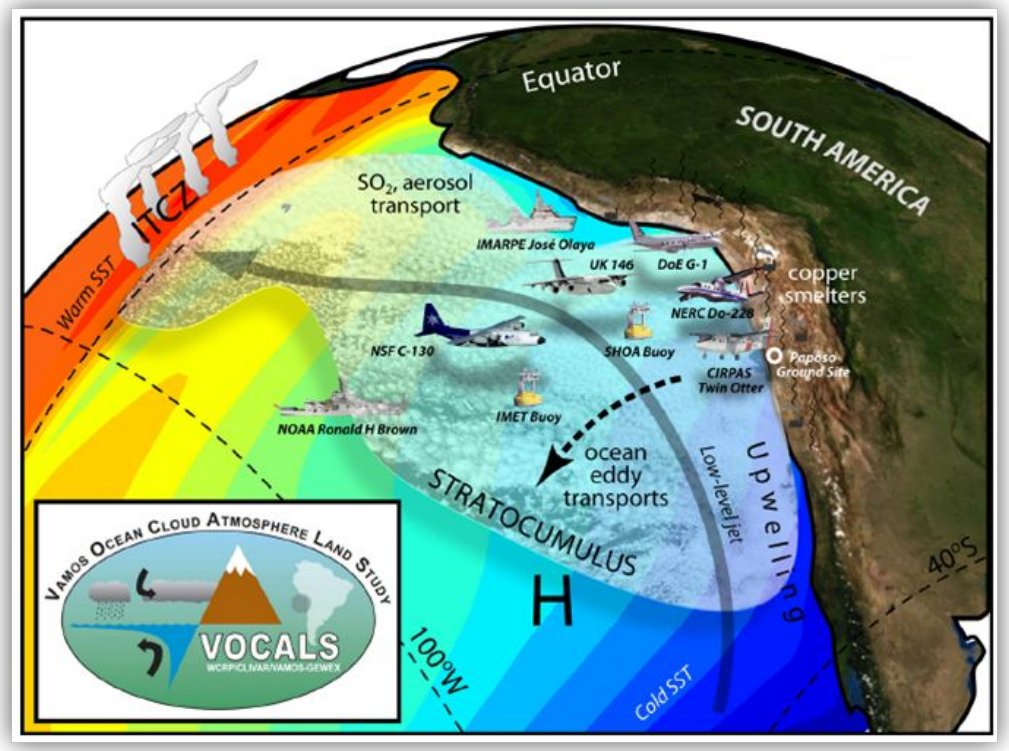
Effervescent ECS nozzle in operation

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)

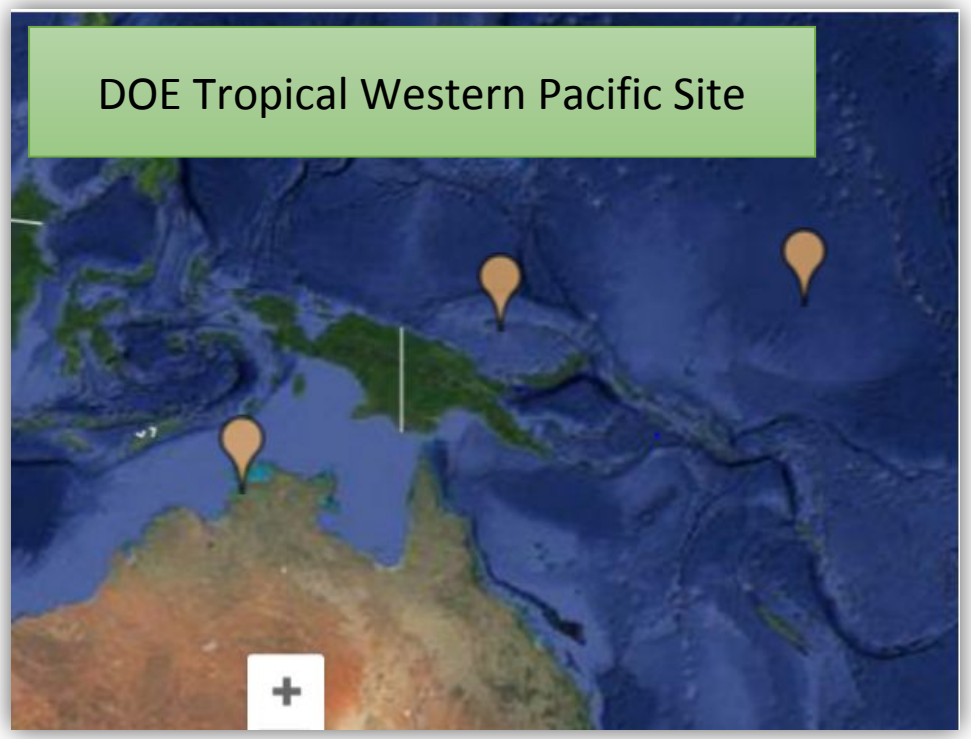


(Snow-making; NOT making small particles)

Our experience with field programs ..



Lead scientist: Rob Wood, UW



Lead scientist: Tom Ackerman, Penn State, DOE

Numerous other cloud/climate experiments in ocean and land locations