MARINE CLOUD BRIGHTENING

Alan Gadian, *John Latham, Mirek Andrejczuk, Keith Bower, Tom Choularton, Hugh Coe, Paul Connolly, Ben Parkes, Phillip Rasch, Stephen Salter, Hailong Wang and Rob Wood* .

Contents:-

- Background to the philosophical approach
- Some L.E.M . and climate model results
- Technological issues.
- Future plans and publications.

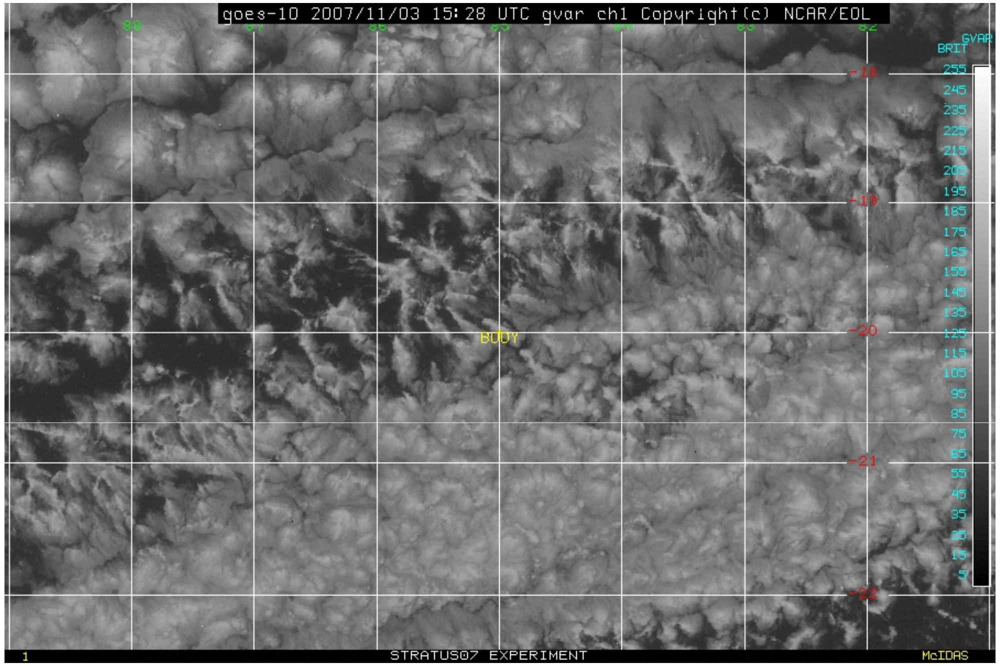
Science Objectives:-

- To explain the science of how stratocumulus clouds can have a significant effect on the earth's radiation balance
- To present some modelling results from Latham et al 2011

Stratocumulus clouds cover more than 30% of ocean surface

Stratocumulus clouds have a high reflectance, which depends on droplet number and mean droplet size.

<u>Twomey Effect</u>.:- Smaller drops produce whiter clouds.



Proposal :- To advertently to enhance the droplet concentration N in low-level maritime stratocumulus clouds, so increasing cloud albedo (**Twomey, JAS, 1977**) and longevity (**Albrecht, Science, 1989**)

Technique:- To disseminate sea-water droplets of diameter about 1um at the ocean surface. Some of these ascend via turbulence to cloud-base where they are activated to form cloud droplets, thereby enhancing cloud droplet number concentration, N **(Latham, Nature 1990 ; Phil Trans Roy Soc 2008 and 2011, under review**)

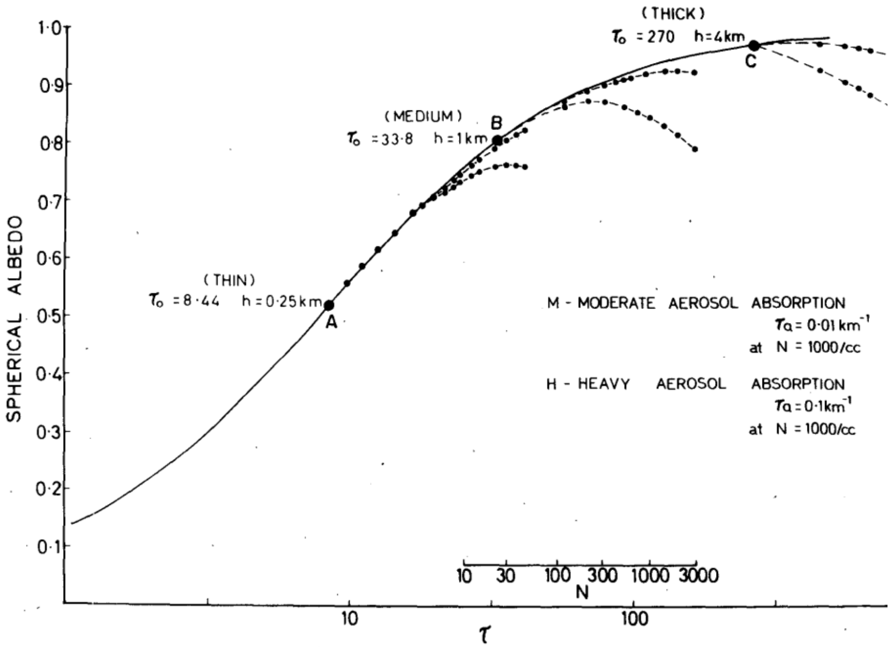
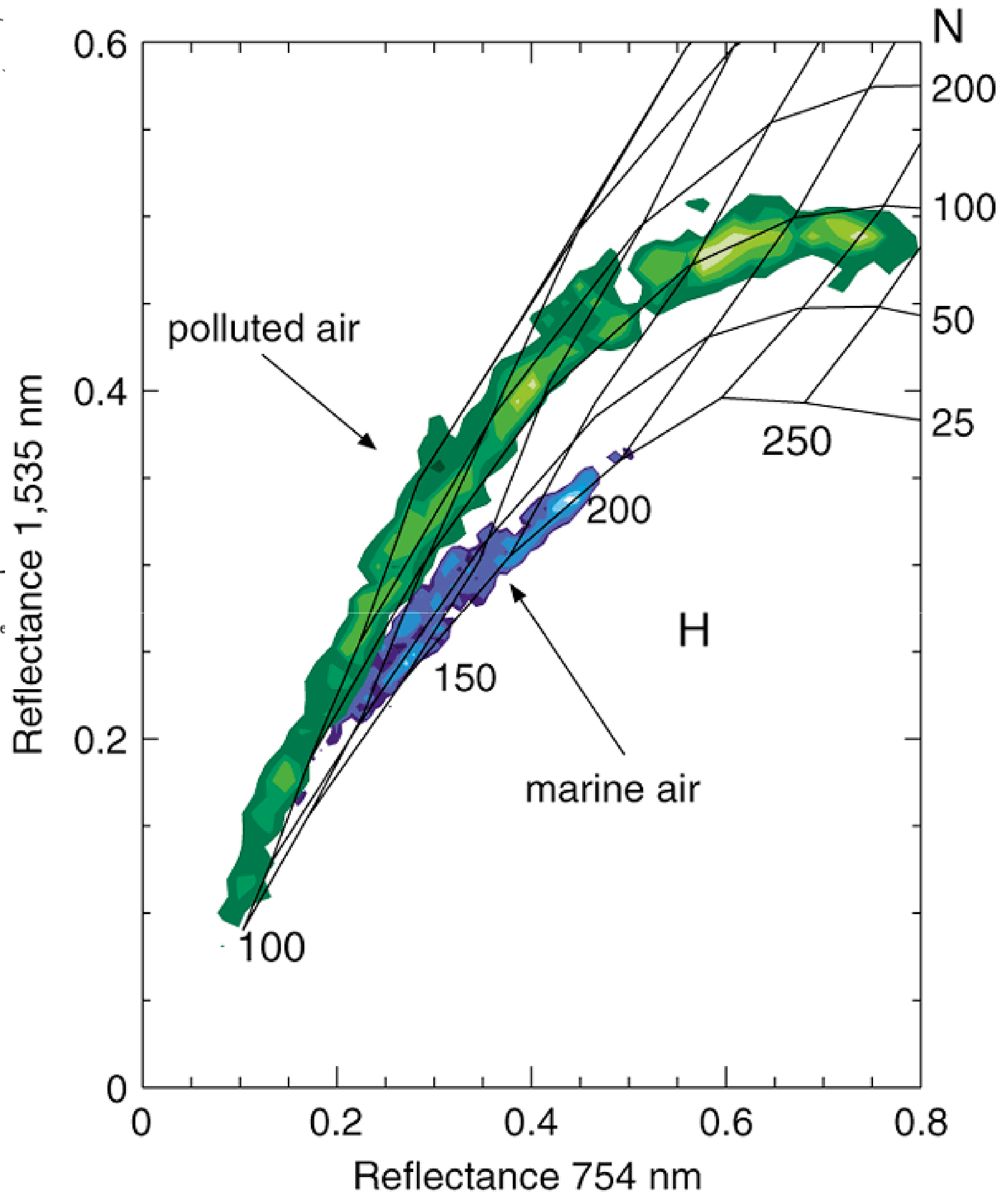


Fig. 3. Numerically computed trajectories corresponding to the schematic curves in Fig. 2, for the change of spherical albe with increasing pollution for thin, moderate and thick clouds.



Above:- Computed spherical albedo for increasing pollution in THIN, MEDIUM and THICK clouds. (**Twomey, JAS, 1977**)

Right:- Frequency distributions of the reflectances at 1,535 nm versus reflectances at 754 nm. From ACE-2. Isolines of geometrical thickness (H) and droplet number concentration (N): higher reflectance in polluted cloud, normalised by a similar geometrical thickness (**Brenguier et al. 2000**).

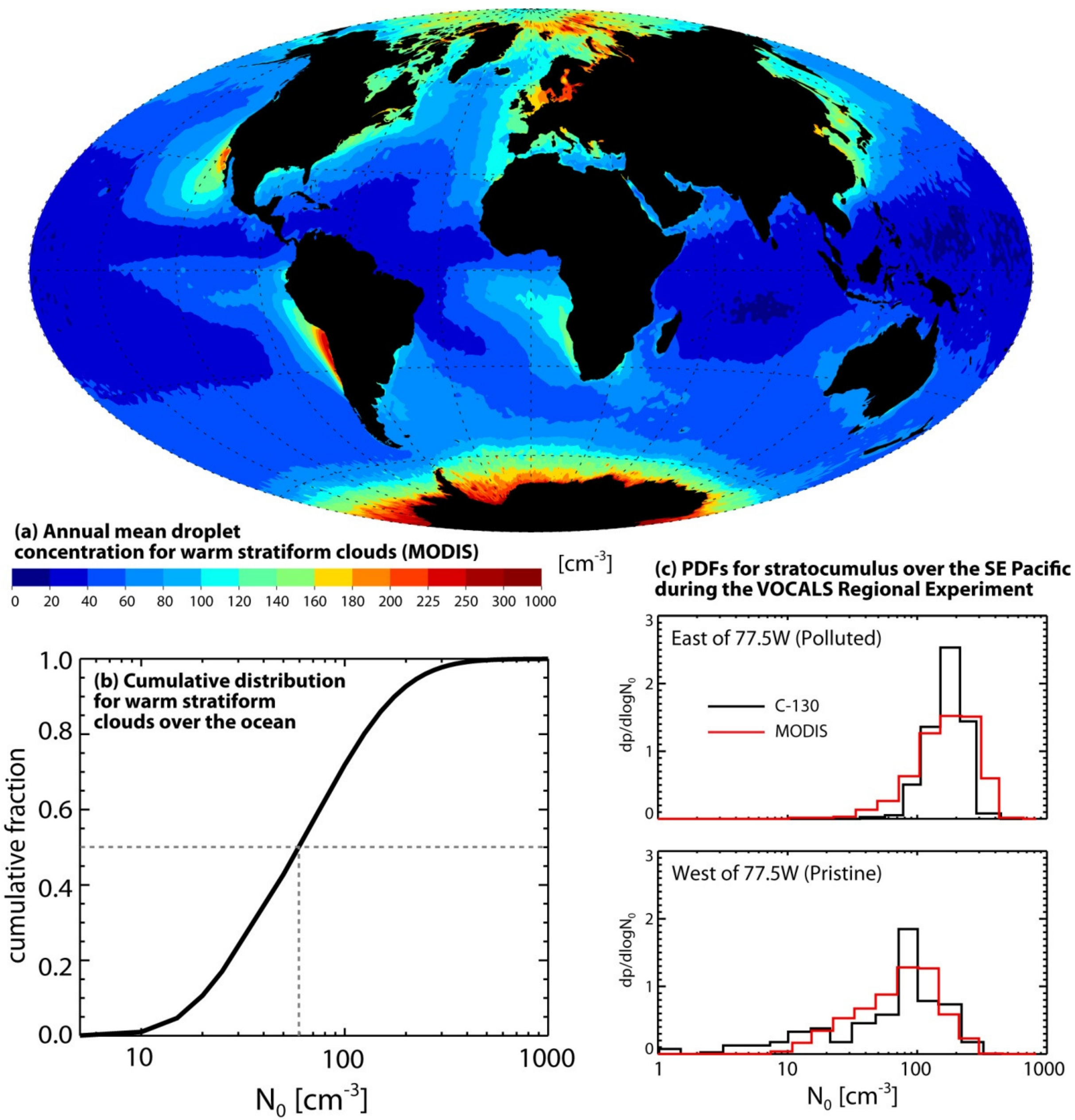


Figure 1. Panel (a): Map of MODIS-derived annual mean cloud droplet concentration N_0 for stratiform marine warm clouds. To be included in the annual mean, the daily warm cloud fraction in 1x1 degree boxes must exceed 50% to capture primarily marine stratocumulus clouds. Panel (b): Cumulative distribution of daily 1x1 degree droplet number, N_0 from MODIS for all ocean points. Panel (c): Comparison of MODIS and C-130 aircraft measured cloud droplet concentration estimates from the VOCALS Regional Experiment during October/November 2008 off the Chilean coast (Wood et al. 2010), for longitudes 70-77.5^0 W (more polluted) and 77.5-85^0 W (more pristine). There is good agreement between in-situ and satellite-derived values which lends weight to the use of these data over the global oceans.

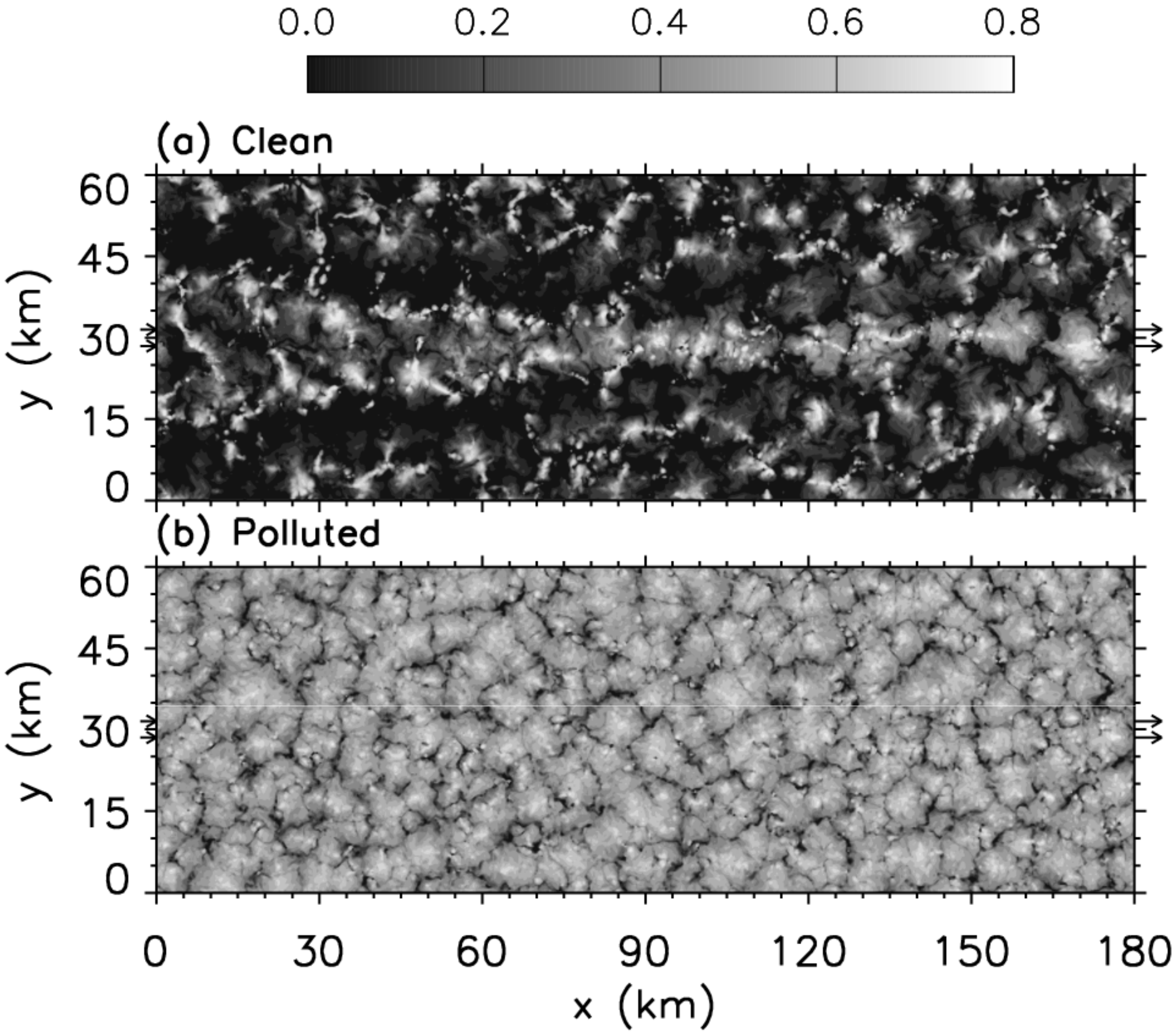
Latham et al. 2011, Phil Trans Roy Soc. .. Figure courtesy Wood

Analytic 1-D (ACPIM) model used to calculate the change in Albedo, ΔA, for clean, medium and dirty air - masses.

ΔA values (in percent) achieved in the 0.2ms^{-1} updraught case for runs where 1000cm^{-3} of NaCl were added in the range 1x10^{-20} to 3x10^{-19} kg.

	Mass (kg)				
Airmass	**1x10^{-20}**	**3x10^{-20}**	**7x10^{-20}**	**1x10^{-19}**	**3x10^{-19}**
Clean	3.9	16	20	25	28
Medium	9.1x10^{-3}	3.8x10^{-2}	5x10^{-1}	1.4	6.5
Dirty	1x10^{-2}	2.3x10^{-2}	4.7x10^{-2}	6.5x10^{-2}	1.8x10^{-1}

(Latham et al, Phil Trans Roy Soc. 2011. Table courtesy of Connolly et al.)

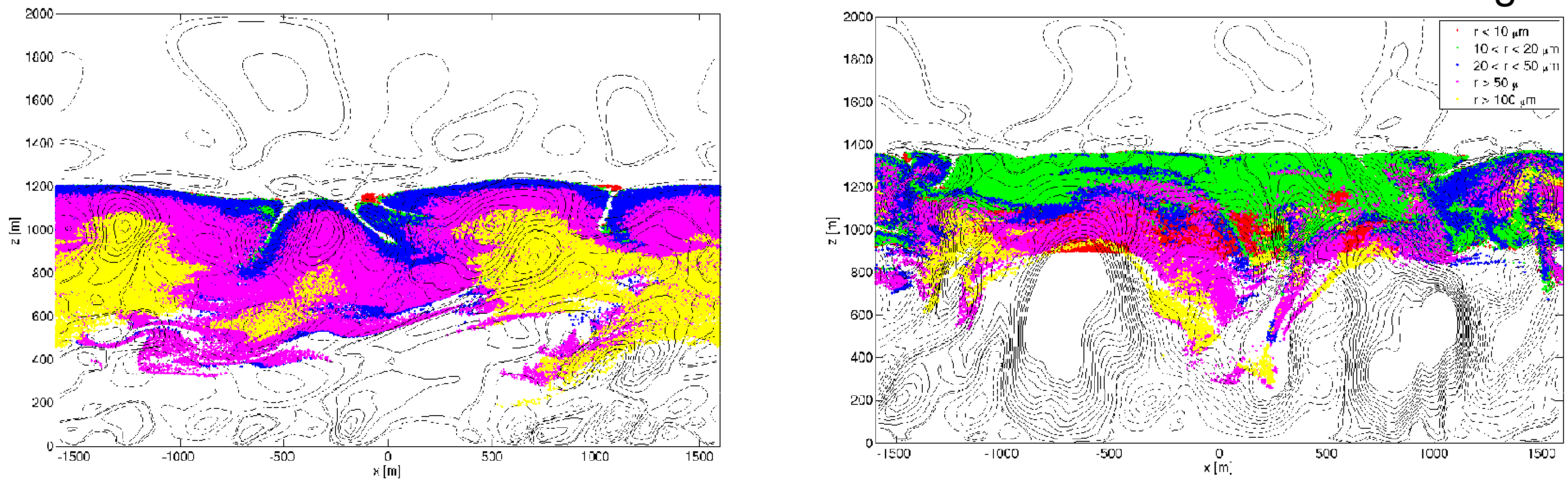


Latham et al., Phil Trans 2011. Snapshots of cloud albedo field when ships pass through the domain once from x = 0 to 180 km, about 7 hours after the start of the simulations. The background aerosol number concentration varies linearly from a lower bound at x = 0 to an upper bound at x = 180 km; (a) clean case 60 – 150 mg^{-1}, and the (b) polluted case 210 – 300 mg^{-1}. Arrows indicate the direction of movement of the ships and the band of ship plumes emitted near the surface. Further details are in the paper. Image from **Wang & Feingold JAS, 2011** .

Typical plots for Lagrangian parcels location and droplet sizes for LOW and HIGH aerosol concentrations**.** **r >100µm , r >50µm, 20 <r<50µm, 10<r<20µm, r<10µm** .

Andrejczuk et al. JGR, 2008, 2010 & 2011

High



Studies of the Albedo response using initial conditions based on the flights of BAe-146. during the VOCALS project. Two different cases from VOCALS observations were chosen. For each case velocity, temperature, water vapour mixing ratio and cloud water mixing ratio profiles were used to initialize model. Two modal log-normal function were fitted to observed aerosol distribution with an aerosol concentration 540 cm^{-3} for HIGH, and 153 cm^{-3} for LOW case. Cloud evolution is driven by the prescribed radiative cooling at the cloud top and the surface fluxes of temperature and water vapour mixing ratio. Without seeding, the model is produced the observed cloud droplet concentration, HIGH 250 cm^{-3} (right panel) and 65 cm^{-3} for LOW (left panel).

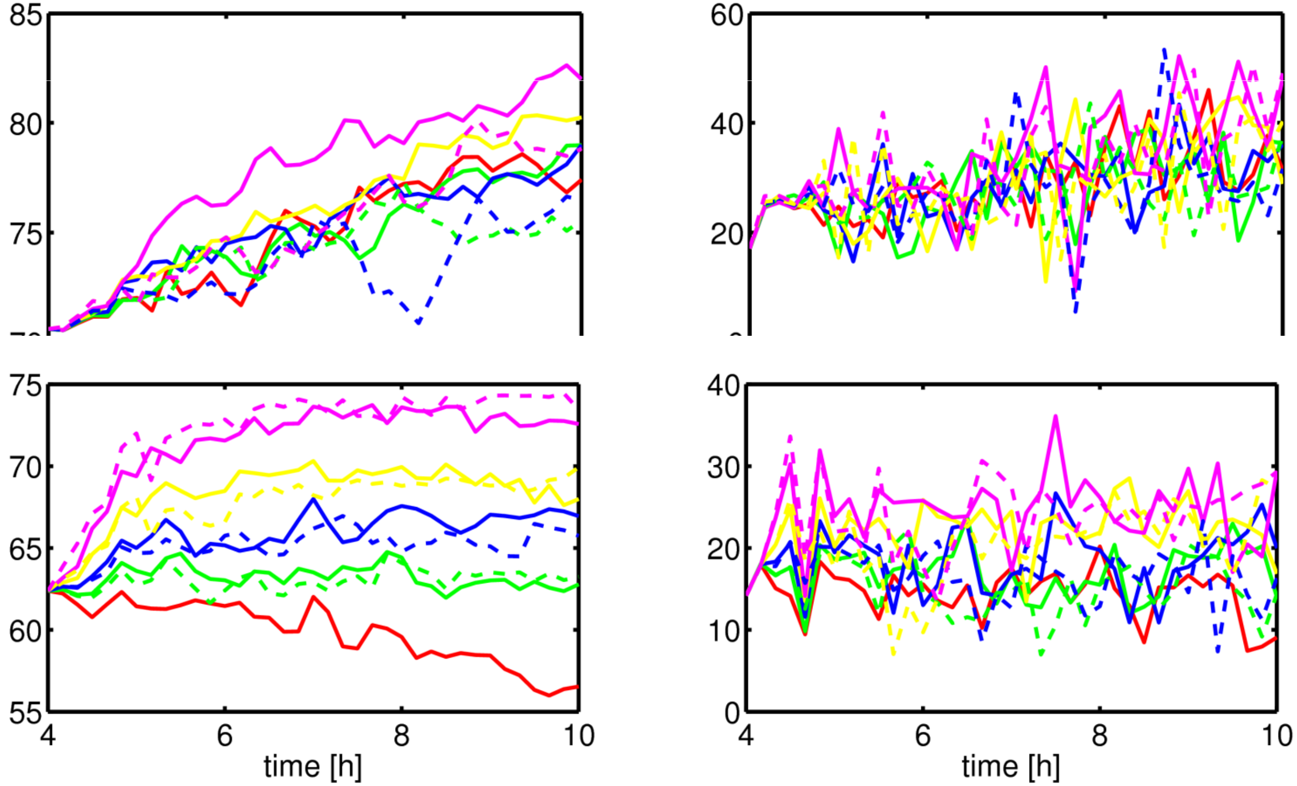
Plot of Albedo/Optical Thickness against time in a VOCALS marine stratocumulus simulations. (***HIDDEN SLIDE***)

Solid line for seeding aerosol of 0.1 µm
Dashed line For seeding aerosol of 0.5 µm

RED ... Control case (no seeding)

+100 cm-3 (GREEN) : +200 cm-3 (BLUE) : +400 cm-3 (YELLOW) : +800 cm-3 (PURPLE)

Albedo Optical Thickness



Low .. (65/cc) Initial aerosol conditions.

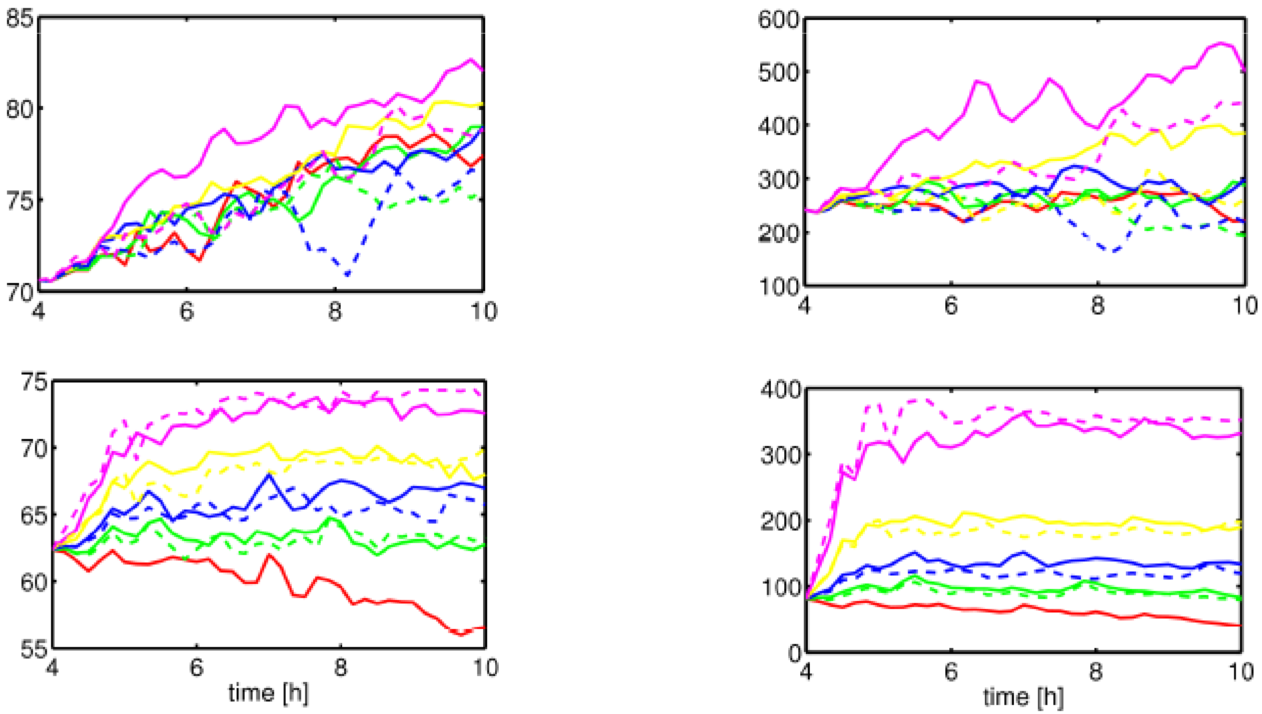
High – (250/cc) initial aerosol conditions.

Plot of Albedo / Droplet Number against time in a VOCALS marine stratocumulus simulations.

Solid line for seeding aerosol of 0.1 µm
Dashed line For seeding aerosol of 0.5 µm

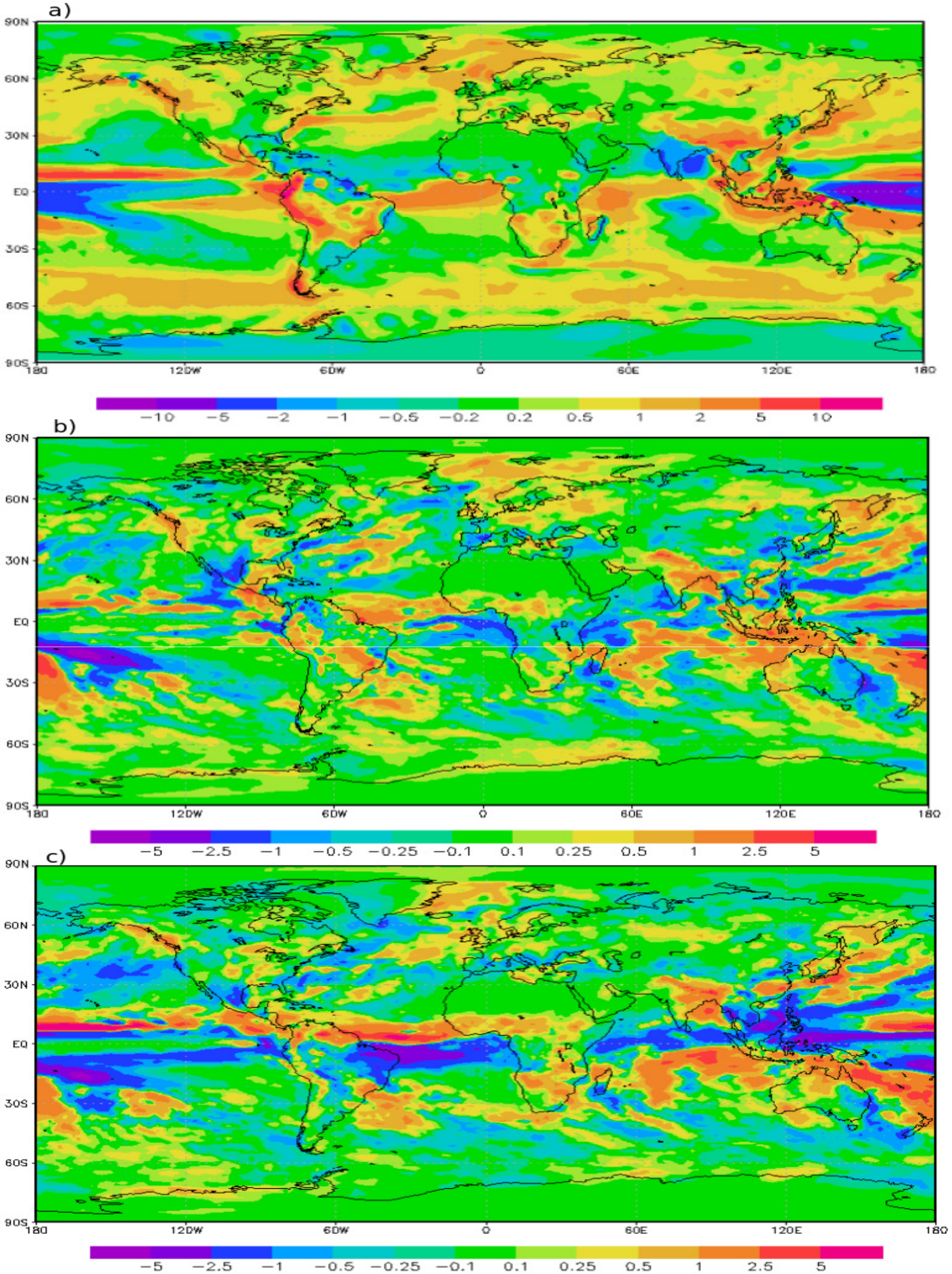
RED ... Control case (no seeding)
+100 cm-3 (GREEN) : +200 cm-3 (BLUE) : +400 cm-3 (YELLOW) : +800 cm-3 (PURPLE)

Albedo, % Droplet Number , cm^{-3}



Low .. (65/cc) Initial aerosol conditions.

High – (250/cc) initial aerosol conditions.



Comparison between model and observed precipitation and investigation into the impacts of MCB on model precipitation (mm/day).

Panel (a) compares the CMAP precipitation dataset with a current carbon dioxide level simulation in HadGEM1.

Panel (b) shows the effect of increasing carbon dioxide from 440ppm to 560ppm within the model.

Panel (c) shows the difference between a MCB simulation, $2CO_2$ and a control simulation.

(Latham et al 2011. Figure courtesy Parkes et al.)

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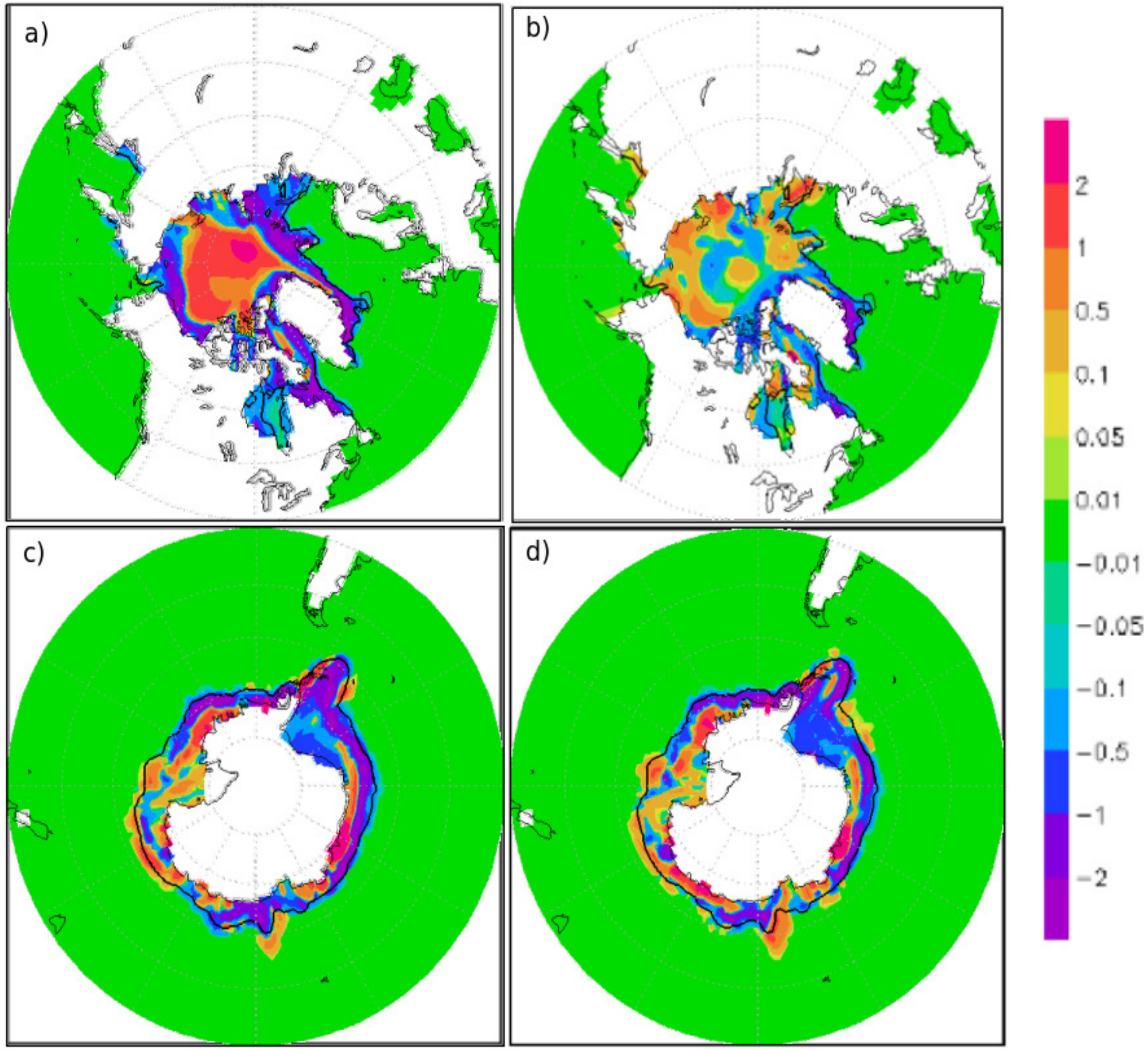
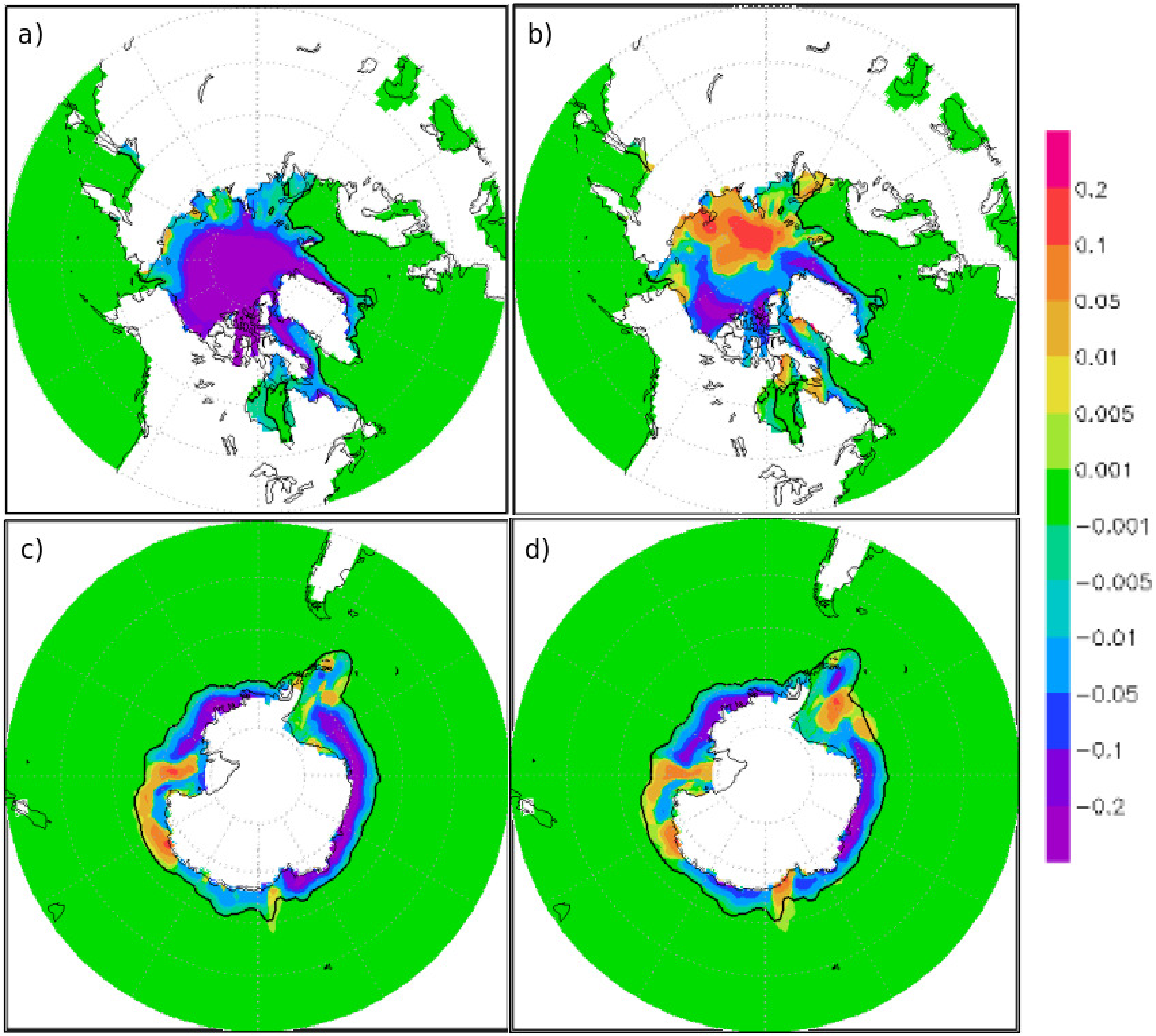


Comparison of the North and South polar sea ice thickness (m) averaged over the summer minimum for the final 20 years of 70 year simulations. Northern minimum is taken as September, and the Southern minimum is taken as March.

Panels (a) & (c) show the difference in the North and South polar sea ice thickness between $2CO_2$ and CON.

Panels (b) & (d) show the difference in the North and South polar sea ice thickness between MCB and CON. The black contour shows the ice limit in CON.

(Latham et al. Phil Trans 2011 . Figure courtesy of Parkes et al)



Comparison of the North and South polar sea ice fraction averaged over the summer minimum for the final 20 years of the 70 year simulations. Sea ice fraction can be interpreted as the fraction of time that ice is present at that location. Northern minimum is taken as September, and the Southern minimum is taken as March.

Panels (a) & (c) show the difference in North and South polar sea ice fraction between 2CO_2 and CON.

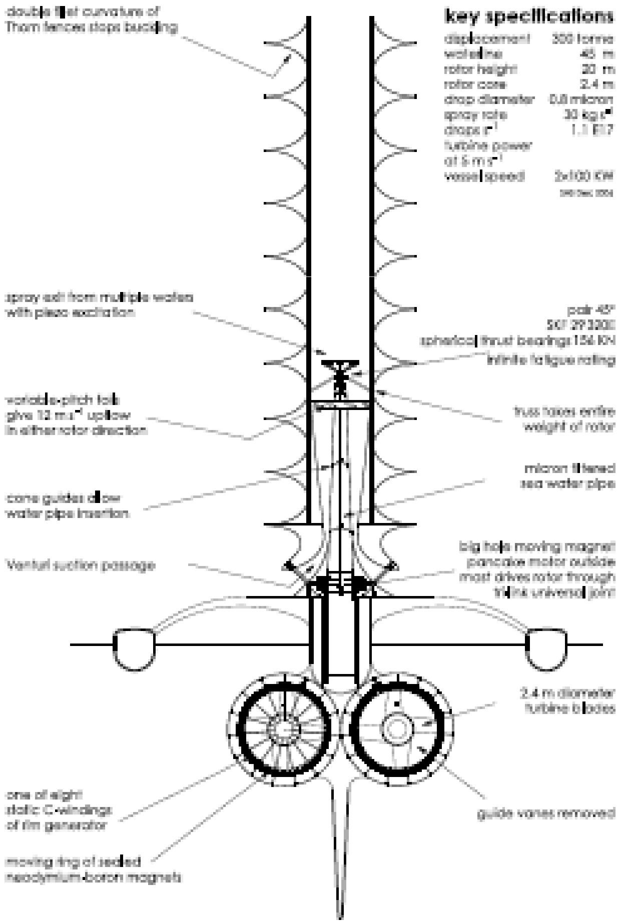
Panels (b) & (d) show the difference in North and South polar sea ice fraction between MCB and CON. The black contour shows the ice limit in CON.

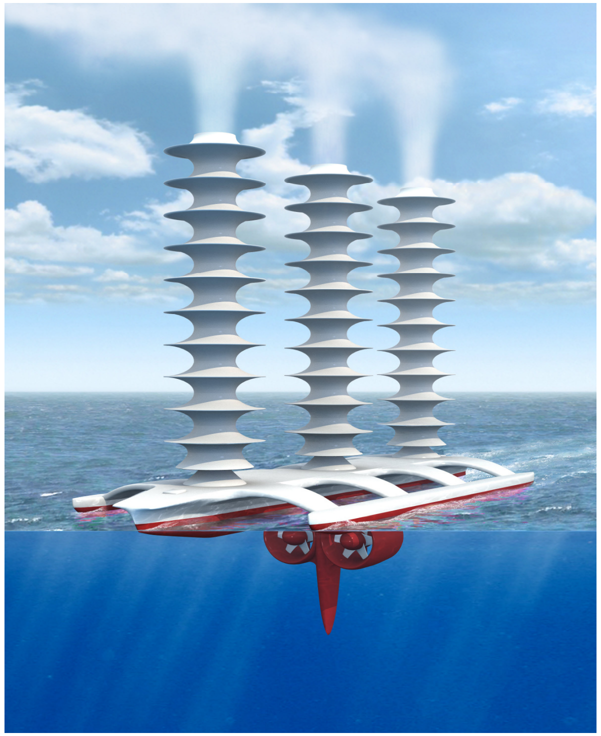
(Latham et al. Phil Trans 2011 . Figure courtesy of Parkes et al)

New Flettner rotor driven ship under construction in Germany

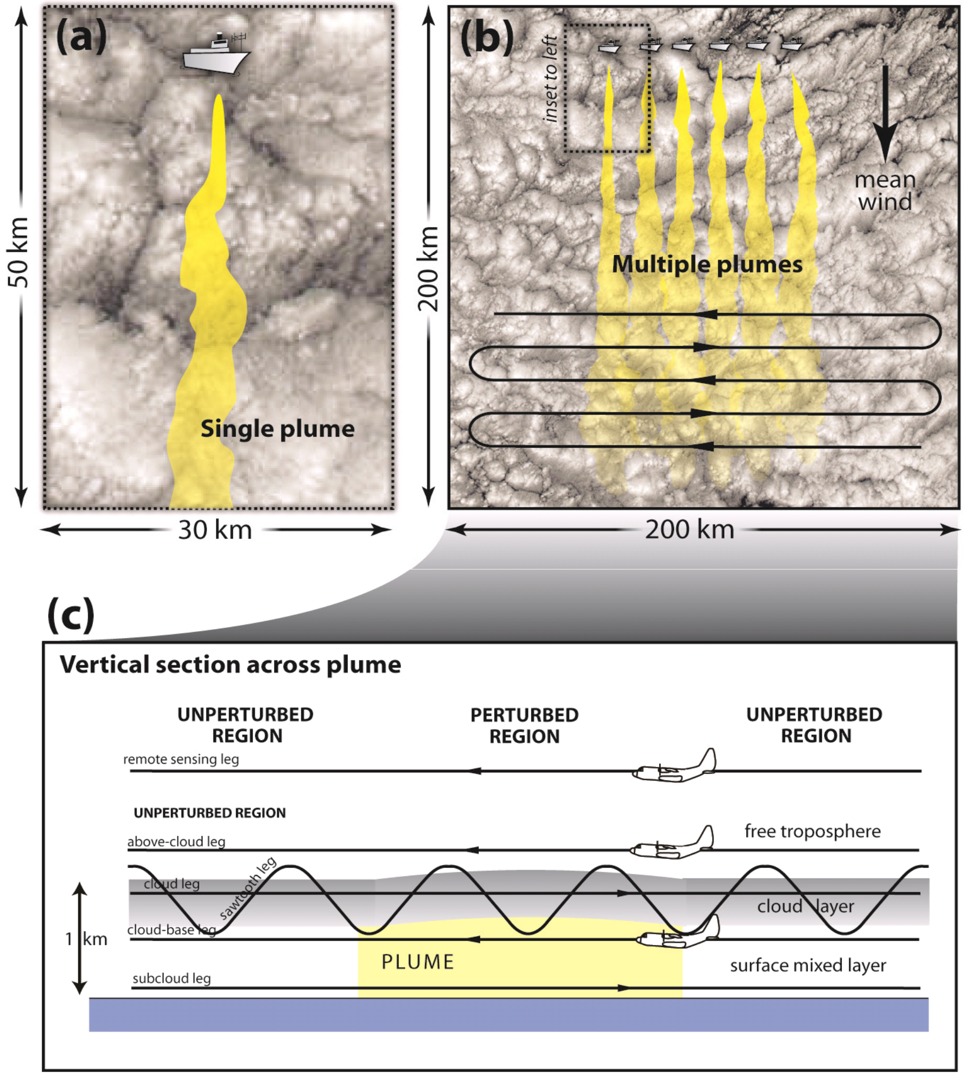
Salter design for a spray mechanism.

(Salter, Phil. Trans. Roy. Soc, 2008





Salter design spray vessel © McNeil



Schematic of the proposed Phase 2 and 3 field testing to evaluate the cloud responses to (a) single plume; (b,c) multiple seeded plumes.

Examination of ship tracks from commercial ships (Durkee et al. 2000) tells us that the plumes spread quasi-linearly with time at a rate of ~2 km hr^{-1} - (Heffter 1965), which for typical wind speeds of 5-10 m s^{-1} is a width of approximately 6-12 km at a distance of 100 km downwind of the source (panel a).

For Phase 3 testing, 5-10 ships (6 shown in example here) would be spaced approximately 10 km apart to generate a single wide plume of 50-100 km wide at a distance of 100 km downwind (panel b). This broad plume and its surrounding unperturbed cloud would be sampled in the cross-wind direction by stacked aircraft as discussed in the text (panel c).

(Latham et al Phil Trans 2011. Figure courtesy Wood and Coe)

Summary:

- A background to the MCB hypothesis, based on the original Twomey proposition, was presented.

- Model results from a 1-D study, some Large Eddy Modelling studies, and HaDGEM1 couple climate model results were shown.

- A technological design for spray generation was presented.

- The hypothes is that Marine Cloud Brightening could provide a real planetary cooling effect**, but** more modelling and analysis is needed.

- An outline suggestion of a field campaign was presented.

- Scientifically … an overall demonstration that Stratocumulus clouds could provide a planetary cooling at least equivalent to the doubling + of CO_2 .