THE REVERSAL OF GLOBAL WARMING BY THE INCREASE OF THE ALBEDO OF MARINE STRATOCUMULUS CLOUD

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Summary

Charles Keeling [Keeling et al 2005] began measurements of atmospheric CO_2 at Mauna Loa in Hawaii in 1958. In June of that year the value was 317.27 parts per million. Month-by-month figures are available from the URL given in the references. The Kyoto agreement was available for signature in June 1992 when the CO_2 concentration was 358.79 parts per million and rising at 1.22 ppm a year. By June 2006, Kyoto plus 14 years, the figure was 384.21 and rising at 1.92 ppm a year.

The present contribution of methane to global warming is about one third that of carbon dioxide [Hansen et al 2005] but measurements of the release from Siberian permafrost [Walter et al 2006] are about five times higher than expected. If the rate of methane release increases it might take over from carbon dioxide as the main driver of global warming, making reductions in the use of fossil fuels less effective. Even people who believe that the wider use of renewable energy sources is the ideal solution think that it is prudent to investigate complementary ways to slow or reverse the increases of global temperatures and have them ready for deployment [Latham 1990] [Crutzen 2006][Angel 2006].

Sean Twomey[1977] showed that the reflectivity of clouds is set by the size distribution of the drops in them. A large number of small drops reflects more than the same amount of water in larger drops. In clean marine air-masses there are fewer cloud-condensation nuclei (often 10 to 100/cm^3) than over land and so the water is shared between drops about 25 microns in diameter, larger than the average 7 microns over land. If the number of suitable nuclei could be increased, the same liquid water content would be shared over a large number of smaller drops and so more of the incoming solar energy would be reflected out to space. Doubling the drop number increases cloud albedo by 5.6%.

Micron-sized drops of salt water are ideal concentration nuclei. When they are sprayed into the marine boundary layer, turbulence will move some into the clouds. The spraying could be done from a number of remotely-navigated, wind-driven sailing vessels dragging water turbines to generate the energy for spray. Depending on assumptions about nuclei concentration, cloud cover, wind-speed, spray-generation efficiency and drop-life, the amount of spray needed to keep pace with, or even reverse, the thermal effects of increases of atmospheric carbon dioxide concentration can be calculated.

The ratio of solar-energy reflected to surface-tension energy needed to create the sub-micron seeds is many orders of magnitude. The technique does nothing for the chemical problems of CO_2 emissions and so is an emergency measure for use if emissions cannot be reduced or if methane released from permafrost takes over from CO2 as the main driver of climate change. Progressive deployment and rapid reversibility are attractive.

Keywords

Global-warming, cloud-albedo, marine stratocumulus, Twomey-effect, permafrost-methane.

1. Introduction

The amount of solar energy reflected from low level marine stratocumulus clouds at present is a function of

- the liquid water content,
- the size of the drops,
- the time of day,
- the latitude,
- the amount intercepted by high cloud,
- the depth of cloud,
- the reflection coefficient of water drops.

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The amount of additional energy we can reflect by exploitation of the Twomey effect will depend on

- the initial concentration of condensation nuclei,
- the NUMBER (but not the mass or volume) of seeding drops,
- the fraction of these that will reach the cloud top,
- the fraction of the sea surface that we can treat,
- the fraction of the sea surface with suitable low-level cloud,
- the life of the drops that reach the cloud.

The energy we need to spray a given number of drops depends on

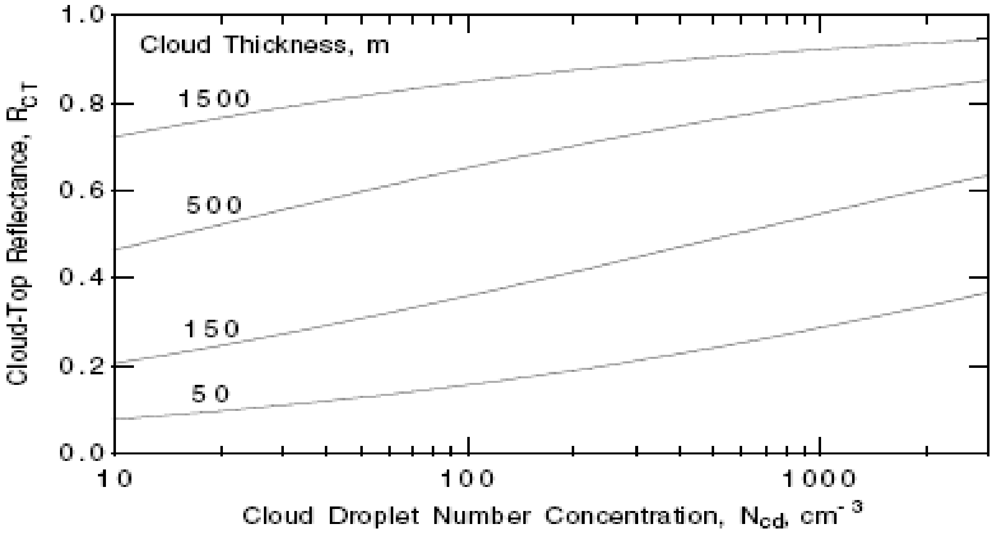
- the surface tension of sea water, 0.078 N/m, slightly higher than for fresh water,
- the diameter of the cloud drops,
- the velocity with which the drops leave the spray-generating mechanism,
- the viscosity loss in any passages forming the nozzle system,
- the height from which the drops are released,
- the pressure drop across pipe-work and any pre-filtering system,
- the energy of any electrostatic charge that might be given to encourage separation,
- the kinetic energy of any airflow needed to aid initial dispersion.

Many of the meteorological parameters are accurately known from satellite observations. The data have been stored in many different forms on different computers in different formats and different sampling rates with different codes. Sortino [2006] has collected and unified much of this in a data-base for the 6596 equal area cells of the ISCCP grid. Access can be made available from the School of Informatics at Edinburgh University. It should soon be possible to make accurate predictions about how much cooling can be achieved by how many spray vessels operating in which regions. Meanwhile this paper makes cooling predictions based on the variation of lumped parameters.

More detail about the background physics of the Twomey effect and some initial computational assessments are in Bower et al [2006].

2.0 Equations

The algebra behind the Twomey effect has been extensively covered in many papers in the meteorological and cloud physics literature. One of the treatments [Schwartz and Slingo 1996] gives explanations which are particularly suitable for newcomers to the field, even engineers with zero prior knowledge of cloud physics and meteorology. Rather than plagiarize their equations we suggest readers download directly from the site given in the references. Their equations have been converted to a MathCAD worksheet which allows easy variation of every parameter and rapid replotting of the effects of any assumption. To confirm the accuracy of the transfer we show, in figure 1, a copy from their paper with the MathCAD version of the same inputs.



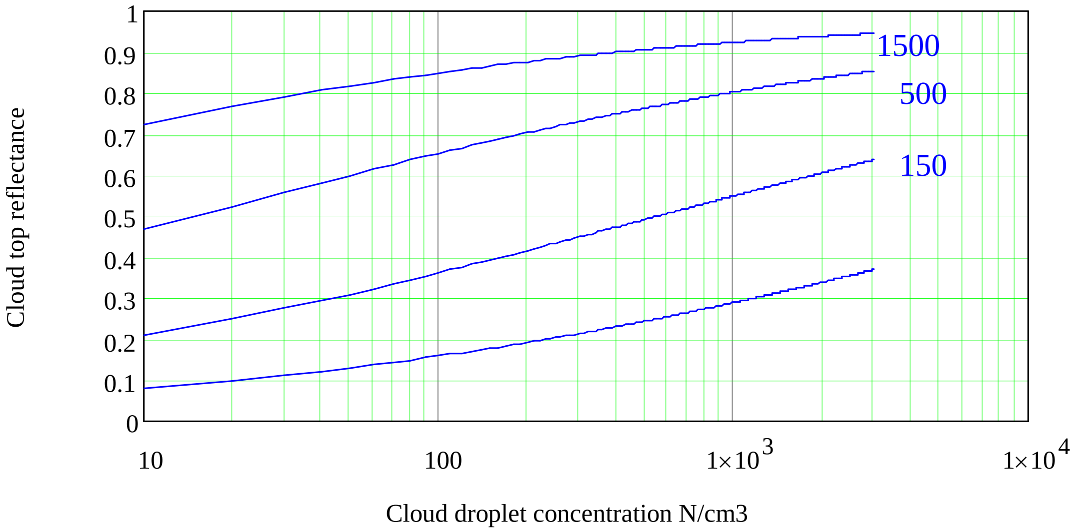


Figure 1. Top: a graph from Schwartz and Slingo 1996 of the cloud-top albedo plotted against the concentration of cloud condensation nuclei for a selection of cloud thickness and a liquid water content of 0.3 cm^3 per m^3. Bottom: the MathCAD results for the same conditions confirming the conversion.

With confidence in the conversion to MathCAD we can use the Twomey equations to produce the graph in figure 2. The rising curves show the increase in global power reflected by cloud tops as a function of spray rate for several assumptions of the initial concentration of nuclei.

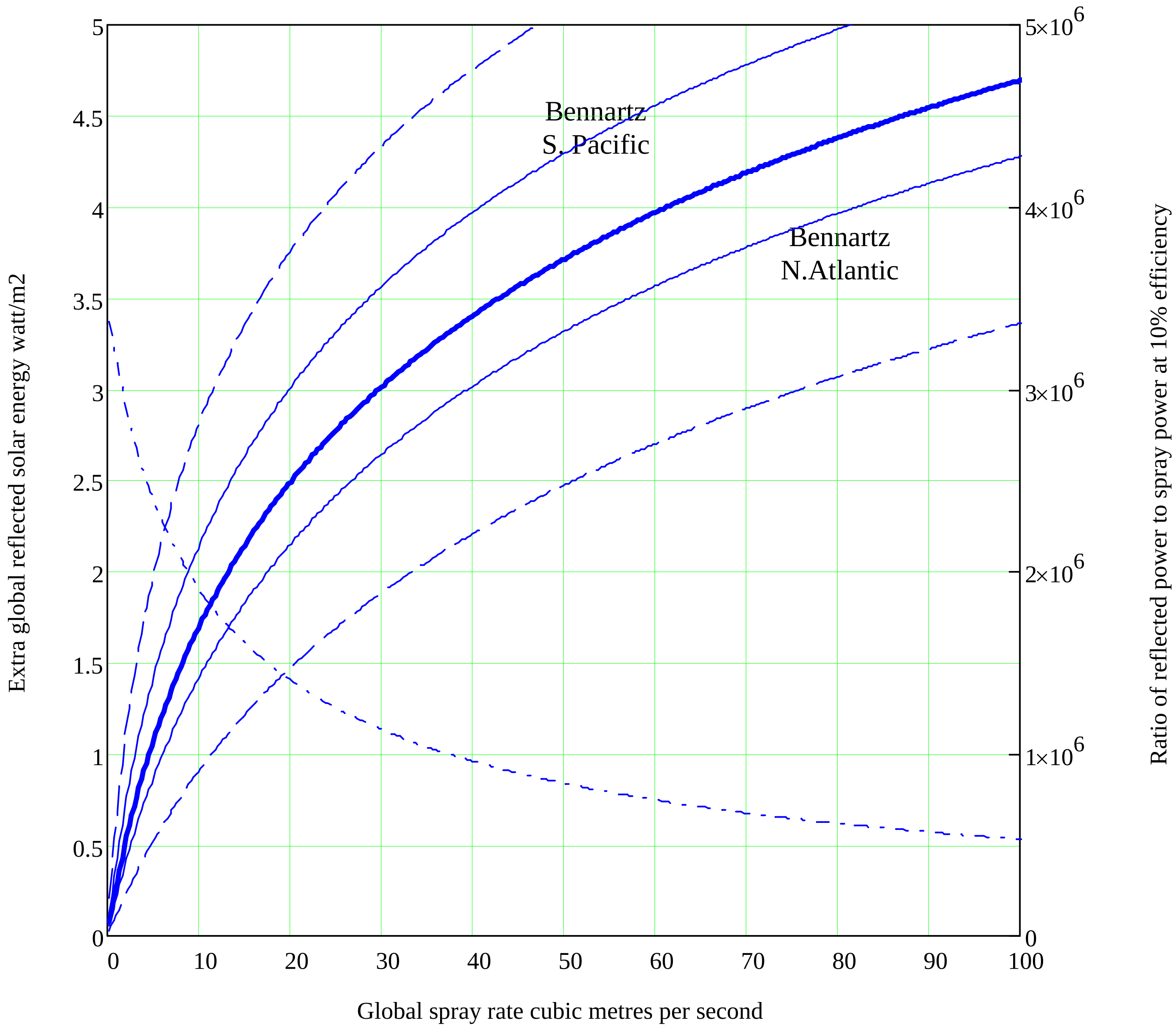


Figure 2. The global effects of spray rate on reflected power density.

The central heavy rising line with the left-hand scale is global power change per square metre for a concentration of cloud condensation nuclei of 64.5 per cm^3 as a function of the spray rate drops. This concentration is the average of the measurements [Bennartz 2007] of 40 per cm^3 for the clean air of the South Pacific and 89 per cm^3 for the dirtier North Atlantic air masses which are shown in the thinner solid lines to either side. The rising dashed lines are half the lowest Bennartz figure and double the highest. The falling dot/dash line and right-hand axis show the ratio of reflected power per square metre to that of the power per square metre needed for spray production assuming an efficiency of 10% referred to the surface tension energy of the drops. The power ratio is clearly very large.

3. Assumptions

Other assumptions are that:

- The mean 24-hour value of the solar input to the cloud top is 340 watts per square metre. This will require seasonal migration of spray vessels to the hemisphere which is in summer.

- The power reduction from the treated clouds is shared with the rest of the global surface.

- The cloud depth is 300 metres.

- The boundary layer depth is taken as 1000 metres.

- The drop diameter is 0.8 microns.

- The liquid water ratio is 0.3 cm^3 per m^3 as in the Schwartz and Slingo 1996 paper.

- The area of the sea being treated is taken as 0.18 of the total global sea area.

- The fraction of this area containing suitable low-level marine stratocumulus clouds but insignificant high cloud cover is taken as 0.3.

- Turbulence produces an even distribution of spray drops through the boundary layer.

- Sedimentation loss of the very small spray drops under cloudless skies can be ignored and that drizzle within the cloud is the dominant removal mechanism which gives an effective drop life of three days.

We would be grateful for suggestions about any other sets of assumptions and can quickly produce the resulting graphs of cooling against spray quantity.

The life estimate is the least certain parameter and we have received advice ranging from 'about a day' to 'a few days' up to 'about a week'. The collision velocities of 30 micron drops are not sufficient to give a Weber number high enough for coalescence but a drop of drizzle can move fast enough to coalesce with all the small drops in its path. Bennartz reports drizzle in 80% of the MODIS observations from the Aqua satellite. If a small drop moves out of a cloud its water will largely evaporate, leaving a concentrated salt residue which is free to go round again. But the residues from a large drop of drizzle may fall fast enough to reach the sea. This life reduction by drizzle is somewhat offset by the clean up of air masses which falling drizzle will produce. Further advice and links to experimental observations would be welcome. It should be possible to make deductions from measurements of cloud aerosol in air masses which have moved from land out to sea at different distances from the shoreline.

Some spray-generating mechanisms have an efficiency of much less than 10% when producing submicron drops. Calculations for the efficiency of a new design of spray generator using electronic micro-fabrication technology suggest an overall efficiency of better than 20% relative to the surface tension energy but will be subject to verification.

Figures 3 to 5 show the effects of variation of the assumptions of drop life, cloud depth and liquid water content.

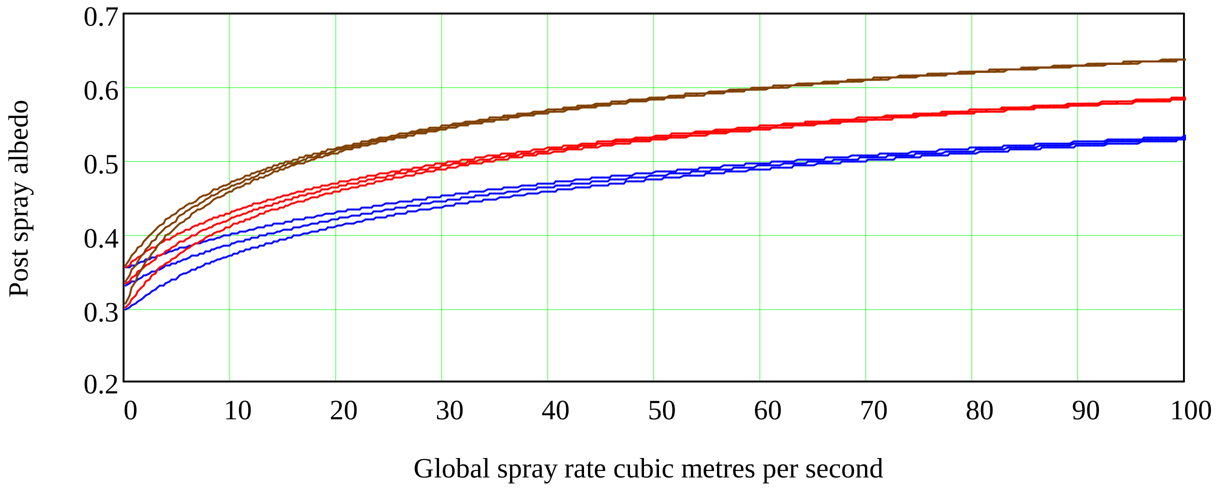


Figure 3. Post-spray albedo for low, average and high Bennartz initial concentrations and drop lives of 1.5, 3, and 6 days. The liquid water is content 0.3 cm^3/m^3

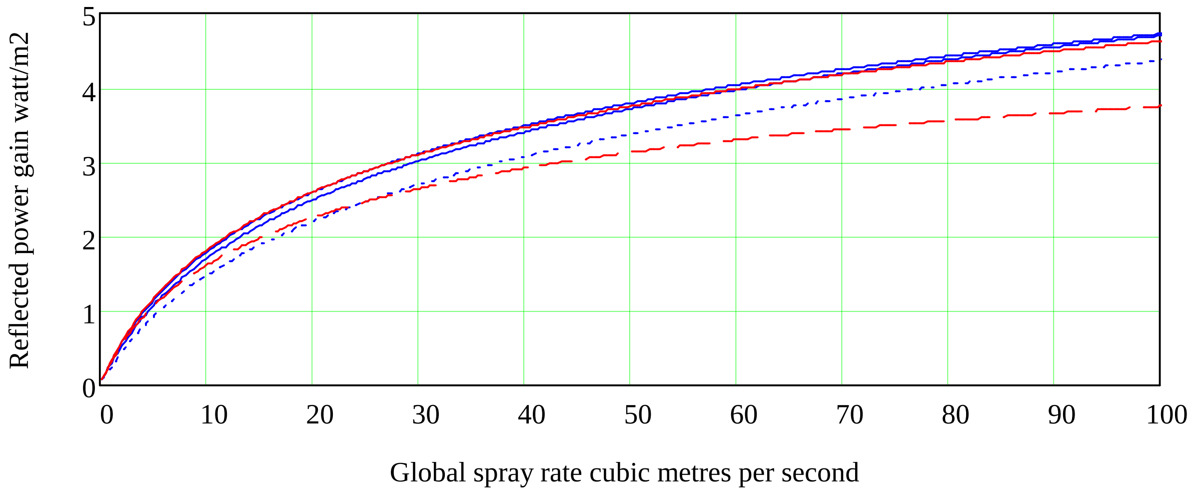


Figure 4. Reflected power for the average Bennatz concentration, 0.3 cm^3/m^3 liquid water content and various cloud depths. There is very little change for the central values of 3, 4, 500 metres but 200 metres (dotted) and 1000 metres (dashed) are low.

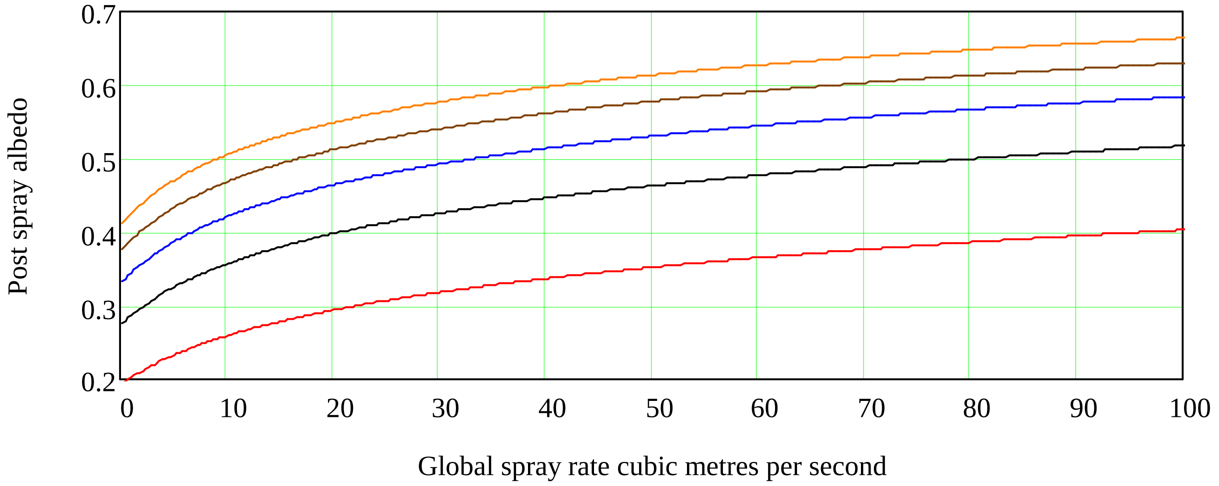


Figure5. Post spray albedo for variation of liquid water content 0.1 to 0.5 cm^3/m^3 and 300m depth.

4. Practical hardware.

The requirement for operations with a good solar input points to mobile equipment which can draw all the spray energy from the wind and so stay on station for long periods. The direction and magnitude of the thrust from a Flettner rotor are controlled by its rotation speed which is much easier to control by a computer in an unmanned vessel than would be the case for a vessel with conventional textile sails. It is possible to apply brakes and, with two or more rotors, to rotate about the vessel centre. Heeling moments are proportional to the first power of wind speed rather than its square and so Flettner-powered vessels should be much safer from capsize in heavy seas. The addition of Thom fences can give lift coefficients up to 20 and lift drag ratios up to 35 so that they can tack much closer to the wind than a vessel with a conventional rig.

Figure 3 is an artist's impression of a spray vessel. Turbines much larger than propellers for a vessel of this size would be dragged through the water to generate energy for spray generation. About 10% of the turbine output would be needed to spin the Flettner rotors. Vessels would be fitted with satellite navigation and an Iridium communications system which would allow them to be directed to suitable spray sites and also to send back to eager meteorologists data on sea temperatures, atmospheric pressure, wind and current velocity and direction, solar input, cloud cover, wave height and period, plankton and aerosol count and even to relay emergency messages. Once at the chosen site each vessel would sail back and forth across the prevailing wind producing a wake of treated air downwind.

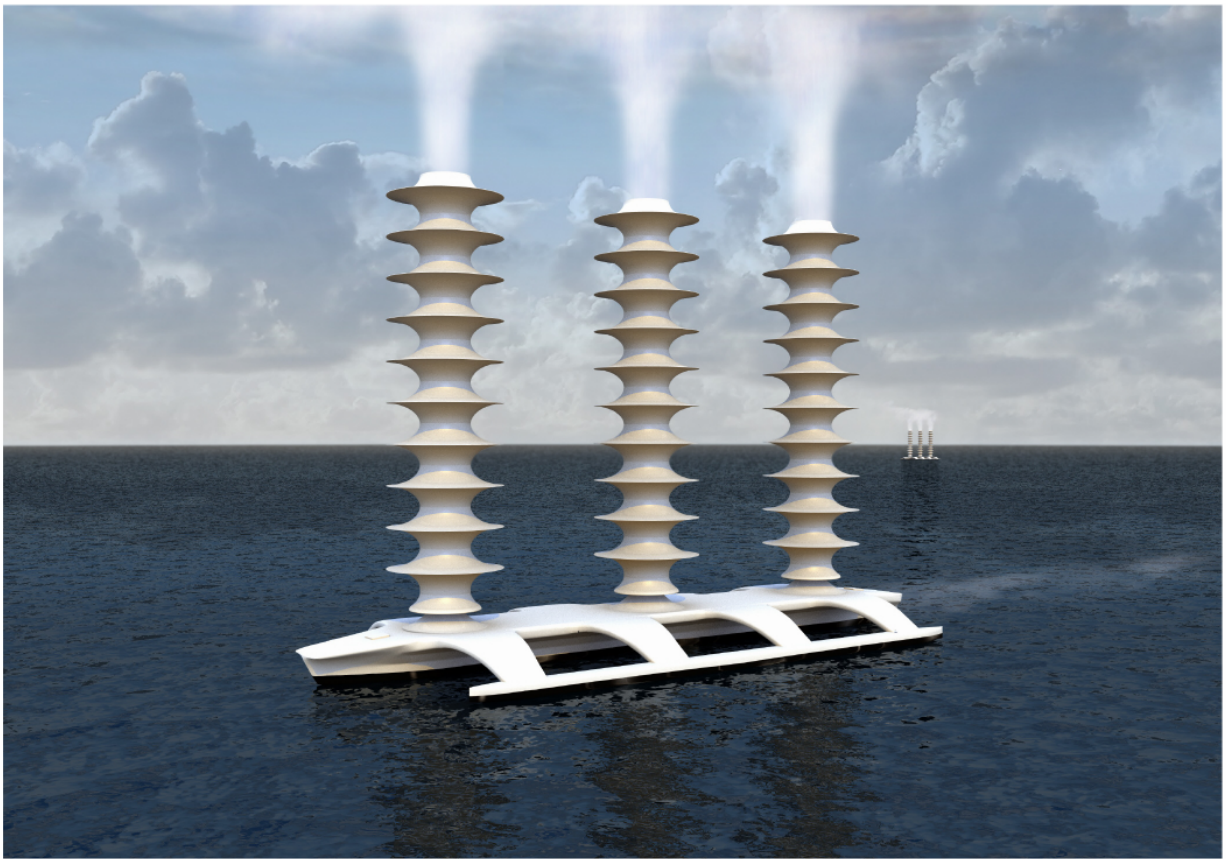


Figure 4. Albedo spray vessels. They would sail back and forth square to the local prevailing wind. Flettner rotors with Thom fences can give lift coefficients up to 20 and lift drag ratios of 35, much higher than cloth sails. Artwork by John MacNeill.

5. Specifications

Initial design work has been carried out. Tentative specifications at February 2007 are as follows:

Water line length	45 m
Displacement	200 tonne
Beam mail hull	2.3 m
Draft main hull	2.1
Beam across pontoons	20 m
Operating wind speed	10 m/sec
Forward velocity generating	7 m/sec
Rotor height	20 m
Rotor core diameter	2.4
Thom fence diameter	5.6 m
Spin ratio core to wind speed	2.2
Rotor thrust	3 by 60 kN
Turbine type	Two contra rotating ducted
Turbine diameter	3 m
Generator type	Wet rotating neodymium boron magnets, static 8-phase pancake windings.
Generator tip speed ratio	1.8
Generator power	2 by 300 kW
Spray technology option 1	Jet to jet collision
Spray rate	10 kg/sec
Drop diameter	1 micron
Water pressure	400 bar
Pump technology	Oil/bladder compression
Collision velocity	>500 m/sec
Air precharge volume ratio	7
Top exit velocity	20 m/sec
Spray technology option 2	Microfabricated thin film nozzle array
Spray rate	20 kg/sec
Drop diameter	0.8 micron
Water pressure	20 bar
Pump technology	Centrifugal

6. Possible side effects

The immediate effect of albedo control will be to cool the water beneath low level clouds. The sea is an excellent store and disperser of heat and is already subject to much larger changes of solar inputs between cloud and no-cloud. In the short term we may be able to do judicious cooling of water flow to particular regions such as the Arctic ocean to restore ice cover and slow the release of methane from permafrost or perhaps to save a coral reef. However this should be seen not as a deviation from, but a restoration to, the former 'desirable' conditions.

Sea air has long been regarded as a benefit to health and already contains quantities of salt very much larger than anything that albedo control could add.

7. Conclusions

Everybody working in the field of climate recovery would prefer solutions to the global warming problem based on the use of non-carbon energy sources. But fourteen years after the Kyoto agreement was ready for signature, the rate of increase of atmospheric CO_2 has itself increased. It is therefore urgent to design and test all possible methods to stabilize temperature for use if the present proposed methods are unsuccessful.

It is technically possible to use albedo control to increase the reflectivity of marine stratocumulus clouds by spraying quite small quantities of sea water into the marine boundary layer. The spray requirement is set mainly by the initial concentration of condensation nuclei and droplet residence time.

As predicted by Twomey, the areas with low initial concentrations of condensation nuclei are the most suitable for albedo increase. The previous uncertainty about these values has been greatly reduced by the recent analysis by Bennartz of Aqua MODIS measurements.

On reasonable assumptions of the present concentrations of condensation nuclei in mid-ocean air masses and drop life, the first global reduction of 1 watt per square metre will require spraying a total of only 5 cubic metres a second. Because of diminishing returns, the increase from 2.7 to 3.7 watts per square metre, needed to stabilize temperatures despite a future doubling of carbon dioxide levels will require an extra 30 cubic metres a second, bringing the total spray rate to just under 60 cubic metres of sea water per second.

If necessary it would be possible to spray amounts sufficient to compensate for five watts per square metre over the entire earth surface.

Operations in water en route to the Arctic Ocean will have secondary benefits in the restoration of ice cover and the reduction of methane release from Siberian permafrost. Operations may also be aimed at endangered coral.

The possibility of initial small-scale tests, progressive introduction, the use of very small quantities of benign materials, six orders of magnitude power gain and rapid shut down are attractive.

Extra observations of surface conditions will complement satellite observations and so be valuable to meteorologists and controllers of the global cooling system.

The next step should be a more detailed analysis of the spay effectiveness in local areas using the coordinated database assembled by Sortino for which some data are still required. The chief remaining uncertainty is the lifetime of small salt residues inside and outside drizzling and non-drizzling cloud.

7. Acknowledgements

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