Sea-Going Hardware for the Implementation of the Cloud Albedo Control Method for the Reduction of Global Warming.

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ABSTRACT. China will be building 1000 MW of coal fired plant every five days for the next eight years and India the same every two weeks. World fossil fuel consumption rose by 4% in 2004. Coal consumption rose by 6%. Our leaders are betting the planet on the hope that carbon sequestration, renewable energy and improved efficiency will be able to compensate. The 2004 increase in the rate of rise of CO2 to 2.5 ppm suggests that the goal has not yet been achieved. If the leaders are wrong and the Siberian permafrost melts to release its stored methane, the global temperature rise will accelerate even more than now. Back-up plans are urgently needed. This paper describes the hardware of one based on John Latham's 1990 proposal to exploit the Twomey effect. Spraying micron-sized drops of sea water beneath marine strato-cumulus clouds will increase their albedo and so reflect enough solar energy back out to space to allow double present CO2 levels with no change of mean global temperature. This paper extends ideas first presented at the Business Beyond Kyoto Seminar, Edinburgh 7th October 2005.

Albedo Basics

The albedo of a body is the fraction of light that it reflects. The albedo of marine strato-cumulus clouds, which cover about one quarter of the world surface, is between 0.3 and 0.7. Sean Twomey (1977) wanted to understand the variations in cloud reflectivity . He found that the albedo was set by the number and size of their droplets. For a given amount of water, a large number of small droplets make clouds reflect more than a small number of large drops. Increasing global cloud albedo by only 1.5% would produce a cooling equal to the warming due to a doubling of current CO2.

John Latham (1990) suggested that the Twomey effect could halt or reverse global warming if we could deliberately introduce sub-micron drops of sea water below low-level marine stratocumulus clouds. Clean marine air masses normally have a deficit of cloud condensation nuclei, often below 100 per cm^3 and sometimes as low as 20 per cm^3. The salty residue left after the evaporation of a small drop of sea water is an ideal cloud condensation nucleus. For clouds in the middle of the albedo range the fractional change in albedo is about one-twelfth of the natural logarithm of the change in nuclei concentration. A doubling of the concentration increases albedo by just over 5.5%.

Spraying of the drops would have to be done where there is a frequent occurrence of the right kind of cloud. Less spray will be needed if the initial concentration of nuclei is low. Latham calculated that the quantities of spray needed in suitable regions are surprisingly small. An annual increase of the spray rate by 10^{18} drops per second would allow the present rate of rise of CO2 to continue with no temperature rise. If the spray were done from 500 new sources each year, spraying one micron drops, the water mass from each would be only one kilogram of sea water per second from each source.

Meteorologists call the lowest few hundred metres of the atmosphere over the sea the marine boundary layer. The average thickness is about 800 metres. Friction between wind and water generates quite high levels of turbulence and so mixing is rapid but stops sharply at the top of the boundary layer. It is the random upward motions, with velocities sometimes over 1 metre per second, which produce clouds and so the distribution of sea water droplets from surface sources will be quite rapid. Drop lifetimes are of the order of a week, so that the control scheme has a rapid response, is locally variable, readily reversible and ecologically benign. Reversibility has a particular advantage.

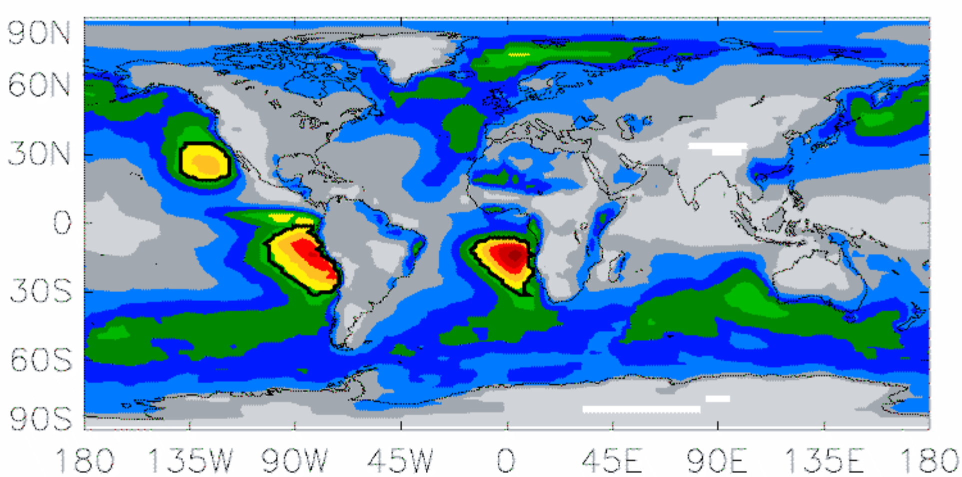

Figure 1. Good places for Albedo cooling are green, yellow and red areas. Low level marine stratocumulus clouds occur frequently of the west coasts of continents and in a band across the oceans of the southern hemisphere.

Energy

As well as having the right kind of clouds, we will need energy to make the spray. The proposed scheme would draw all the energy from the wind. Numbers of remotely controlled spray vessels would sail back and forth, perpendicular to the local prevailing wind. The motion through the water would drive underwater ‘propellers ’ acting in reverse as turbines to generate electrical energy needed for spray production. These would look larger than the propellers needed for propulsion of a similar sized vessel. Batteries would store energy for intricate manoeuvring or for several hours of propulsion in windless conditions. Each yacht would have a global positioning system, a list of required positions and satellite communications to allow the list to be modified from time to time, allowing them to follow suitable cloud fields and to return to land for maintenance.

The problems of the remote operation of ropes and reefing gear would be avoided if we use Flettner rotors instead of sails. These are vertical spinning cylinders which can produce forces perpendicular to the apparent wind direction which are very much larger than those from textile sails. They were used successfully for ship propulsion in the 1920s, Seufert and Seufert (1983). They allow a sailing vessel to turn about its own axis, apply ‘brakes ’ and go directly into reverse. Anton Flettner built two sea-going ships. The first crossed the Atlantic in 1926. He obtained orders for six more, only to have them cancelled as a result of the 1929 depression. The rotor system weighed only one quarter of the conventional sailing rig which it replaced. Flettner used drums of steel and later aluminium. Today much lighter ones could be built with glass or carbon -reinforced epoxy materials. The power to spin the rotors was about 10% of the power of the ship ’s engines. Figure 2 shows an artist ’s impression of the proposed design.

It is the NUMBER of condensation nuclei disseminated, not the mass of spray, which matters. The inescapable minimum energy required for the ideal spray generator is the amount required to create the new surface area against surface tension. The surface area of a 1-micron drop is 3.14×10^{-12} m2 and the surface tension of sea water is 0.078 N/m so the very minimum energy is 2.45×10^{-13} Joules per drop. This amounts to only 245 kW additional power to cope with present world annual CO_2 increases. However the energy requirement of practical spray generators now being designed is likely to be at least 50 times more. Even so the ratio of the wind power required to make the spray relative to the reflected solar power is probably between 6 and 8 orders of magnitude.

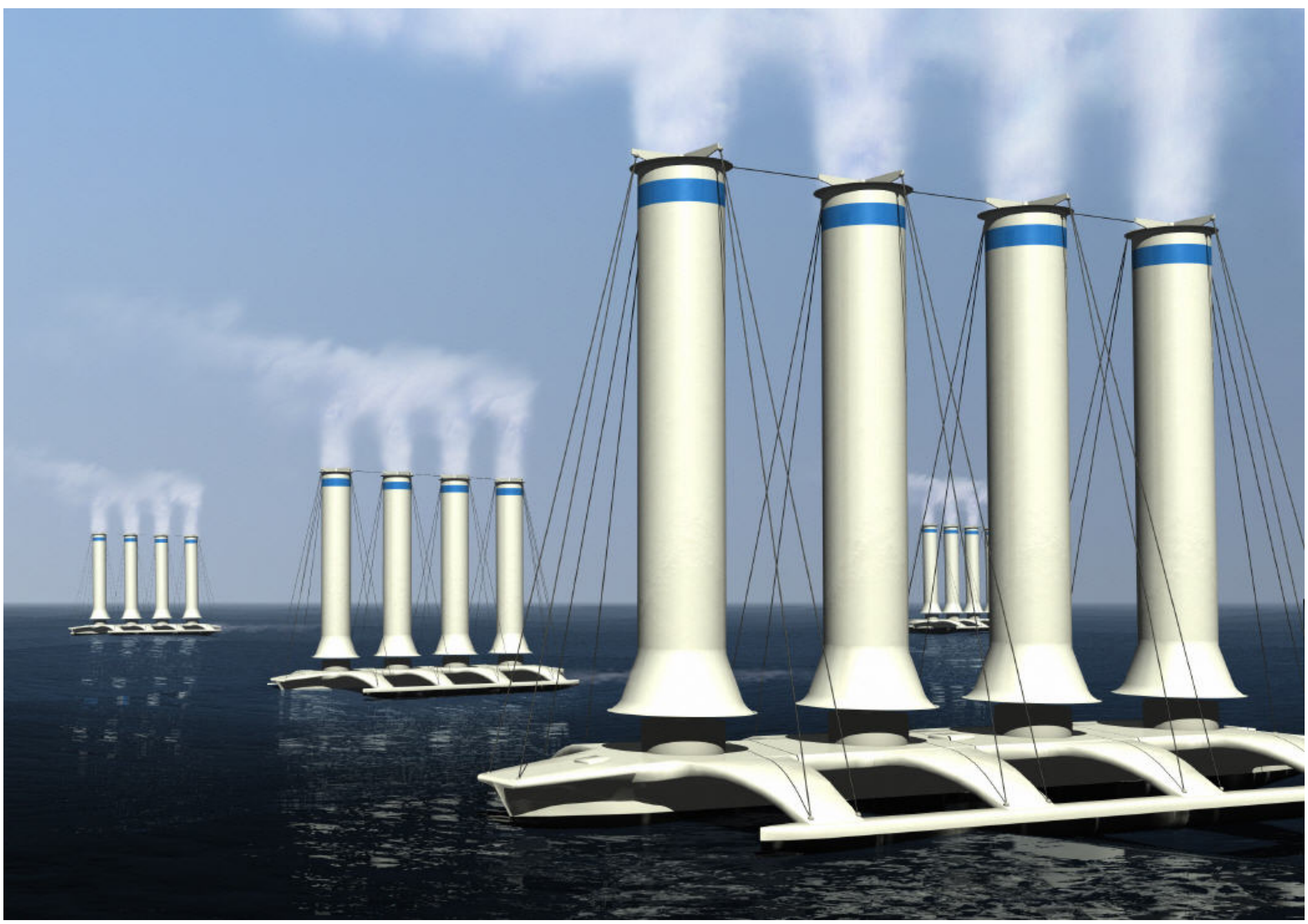

Figure 2. Albedo spray vessels. They would sail back and forth square to the local prevailing wind. The spinning cylinders are Flettner rotors which can give lift coefficients up to 9, much higher than cloth sails. Artwork courtesy of John MacNeill.

Spray technology.

Many spray generation methods are available. The commonest is a Venturi passage sucking liquid into a high velocity air stream as used in carburetors but this produces a very wide range of drop sizes.

A very narrow range of drop diameters can be achieved if a jet of liquid is directed to the centre of a spinning disk. The liquid is centrifuged out to a sharp-edged rim from where it will be thrown off when centrifugal force exceeds surface-tension force. Walton and Prewett (1949) give the equation for drop diameter as a function of density, surface-tension and spin speed. The technique is excellent for drop diameters down to about 30 microns but the disk speed required for the Latham diameters is too high for practical wheels.

Ultrasonic atomisers are used for dispensing chest medications and even for mist effects in stage performances. A submerged piezo-electric actuator induces short-wavelength capillary waves known as Faraday waves at the liquid surface. If these are steep enough, drops are thrown out from wave crests. Viscous losses in such short waves are rather high but we are trying to reduce them.

The behaviour of drops colliding with one another depends on a parameter known as the Weber number. This is drop diameter times density times the square of velocity divided by the surface tension and is the ratio of kinetic energy to the surface-tension energy. For values below one, the impact is not enough to break the air film between drops and so they bounce apart. For values between one and ten, the drops will probably coalesce. For values much above ten, drops will break up into smaller ones with larger numbers of smaller drops being created by higher Weber numbers. It may be possible to use electrostatic forces to make drops collide with one another or to bounce between parallel walls kept at opposite voltages. This would be much easier if we can produce a material with hydrophobic but electrically conducting properties which will not be contaminated by prolonged impact of seawater. The search continues for durable and energy-efficient spray generation technology which can produce micron-sized drops with a narrow spread of diameters.

The spray equipment is being designed to fit inside a Flettner rotor which would be open to air at top and bottom. At the top of the rotor would be a fan, preferably spinning at the same speed. A sensible guess for the blade pitch suggests that the axial air velocity up the rotor will be about half the peripheral drum speed. This is likely to be around three times the wind speed and allows us to calculate the size of the largest drop which would be lifted by the Stokes force. An upward velocity of 5 metres per second will produce a Stokes force sufficient to lift any drop smaller than 400 microns against gravity.

Demonstration

Before anyone will pay to build one spray vessel, let alone one hundred, there must be clear proof that the system will work as claimed. The proof should be in visual form, easily understood by non-technical decision-makers. It could be a satellite photograph of an unnatural pattern of cloud brightness. However, image contrast will have to be much higher than the 6% increase needed to offset the effects of double present atmospheric CO_2 concentration. Under good laboratory conditions with straight stripe patterns the human contrast detection threshold is about 10%.

Figure 3 shows mathematical shapes intended to represent the wakes of two point sources at sea level with a standard deviation divergence angle of 3 degrees and three rings representing the wakes from the flight path of a circling aircraft. The cross sections are the familiar bell-shaped Gaussian curve.

Figure 4 shows a satellite photograph of marine stratocumulus clouds near Madeira with maximum albedo set to 0.7. The brightness of the cloud image has been multiplied by 0.1, 0. 2 and 0.3 of the flight path image and 0.3 of the two wake images in figure 3. This shows that the demonstration must achieve albedo increases of at least 1.2 to convince a non-technical decision maker. This will require an increase of the concentration of cloud condensation nuclei of about 11. This increase is far above what any final equipment would have to do, but possible if the experiment is done with very clean air masses.

Design choices and parameters

The **spray sites** should have frequent partial cover of marine stratocumulus clouds, steady wind speeds but not hurricanes, low initial levels of cloud condensation nuclei and not too much other marine traffic. If we can achieve long service intervals the distance to base does not seem important. This confirms the selection of the trade wind belts in the southern oceans. There may also be a special need for operations round the arctic ocean because of the added reflectivity of ice cover.

There has been a long term trend in naval architecture for **vessel size** to increase. This is because of the relationship between water line length and wave drag. Larger vessels can carry more sails or Flettner rotors and develop more power. However too much spray at one point will saturate the local clouds and so be ineffective especially because of the logarithmic term in the Twomey equation.

The **vessel number** should be chosen to achieve an even distribution of a low concentration over a wide area. With a 3 degree divergence of the standard deviation of the spray concentration we get a merging of wakes after a down-wind range of 10 times the source separation distance.

The power into the propeller/turbine depends on the product of **vessel speed** and **rotor thrust,** which will itself depend on the square of vessel speed so reasonably high speeds, just short of the sudden rise in wave drag, are attractive for energy and smaller turbines.

Vessel geometry could be mono-hull, catamaran, trimaran, proa or even a kite tied to a vestigial keel in the water. The mono-hull suffers more than other designs from water line-length effects on drag, provides more machinery space than we need, rolls a good deal in beam waves but has good recovery from extreme roll. The catamaran suffers less from wave-making drag caused by short water line length, rolls much less but recovers less well from extreme roll. However it seems less suited for the centrally placed machinery below Flettner rotors. This suggests that a trimaran configuration is attractive.

The **beam** of the vessel and the side-floats are chosen to give adequate righting moment at maximum rotor drag force and wave slope. There is a sharp reduction in righting moment when one side-float becomes fully submerged or the other fully out of the water.

Figure 3. Mathematical wake patterns representing stationary sources and aircraft.

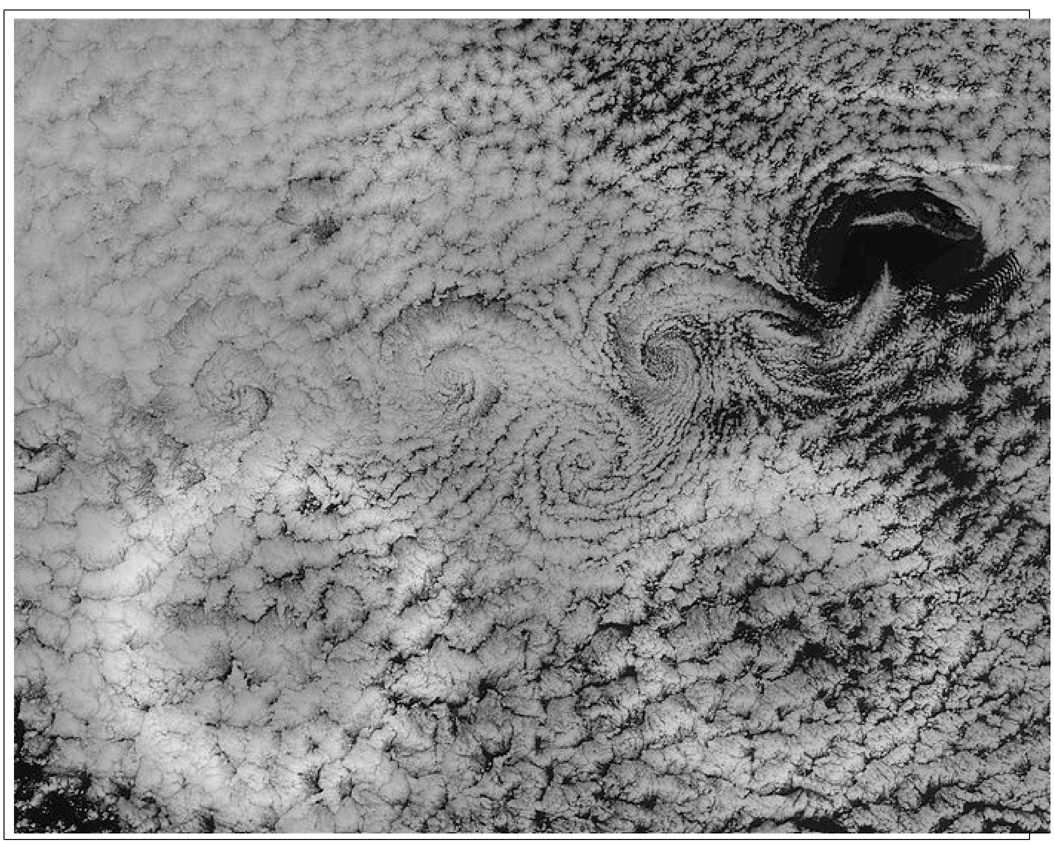

Figure 4. The superposition of wake brightness from figure 3 on marine strato-cumulus clouds near Madeira. Contrast would have to be increased by about 1.2 for a convincing result.

The need for remote control rules out traditional fabric **sails** whose only advantage is that they can be stowed by the crew. The first design ideas used solid wing sails rotating about a vertical axis slightly forward of the centre of pressure with the angle of the wing to the apparent wind set by a torque rather than a position command. Removing the torque lets the sail head directly into the wind with much less drag than a bare mast so wing sails have very attractive survival features. However it was not so easy to combine a wing sail with a spray generator. Flettner himself had considered wing sails but abandoned them for rotors. His circular section is a much better beam than a wing sail.

The useful thrust from a Flettner rotor depends on the product of **length** and **diameter** but short fat ones will suffer losses analogous to the tip vortex loss of an aircraft wing. Flettner used end plates. It would be interesting to look at conical dunce 's caps for the rotor top. A length of 18 metres and a diameter of 3 metres would be about the largest convenient for road transport. We have to expect that rotors will interfere with one another if they are too close, just like the wings of a biplane. Flettner used two rotors on his first ship and three on the second. With two, the ship can turn about its own axis. With three some functionality would remain after the failure of one. Three or four seem right.

The rotor thrust rises with the first power of **spin speed** times the apparent wind velocity rather than its square. However the power needed to drive the rotor is likely to rise with the cube of the spin speed and so there is an incentive towards rather large but slow rotors. Numerical work by Mittal and Kumar (2003) at low Reynolds numbers shows that rotor surface speeds below two or above four times the wind can induce quite large oscillatory forces analogous to von Karman vortex shedding on a non-rotating cylinder. We are trying to predict effects at very much higher Reynolds numbers.

If the **batteries** are sized to give adequate manoeuvrability and endurance for the final approach to harbour at low speed they will certainly be adequate for going about at the end of each leg of the spray path.

The initial choice of **hull material** for the experimental vessels will be steel because of the ease of welding attachment points and drilling holes. Later small batches will be in glass-reinforce plastic. However for large production numbers the low energy content and excellent endurance in sea water of ferro-cement is of interest.

The **generator** must operate over a wide range of speeds and power levels. A poly-phase permanent magnet machine using moving neodymium boron magnets and static coils built into the rim of the rotor seems best. Switching mode electronics with series/parallel change-over to cover a wide power range, will convert this to DC for battery storage.

Motors for driving the several types of pump for water and air can be standard induction machines running on a nominal 50 Hz supply from an inverter. However there is considerable competition for space at the bottom of the Flettner rotors for locating bearings, mechanical and electrical power instrumentation, control and fluid passages. Although there are commercial designs of vertical axis induction motor with hollow shafts on the market, the vessel design looks less congested if we develop a special permanent-magnet rim-motor built into the entry passage of each Flettner rotor and driving it directly with no gears. It can run on direct current with local commutation depending on the angle of rotation.

Standard global positioning systems are fine for **navigation** with changes in the required mean position communicated by satellite. However most of the communications will be meteorological data on atmospheric pressure, air and sea temperature, solar input, the speeds and directions of current and winds, perhaps even plankton count, being sent from vessels back to meteorologists and biologists ashore who will greatly appreciate hundreds or thousands more observation sources.

The dispersion of plumes can be very complicated and is explained in (Anon 1999). For engineering purposes we can simplify some complicated relationships to a single parameter of the angle by which the standard deviation of the concentration of nuclei diverges from the mean wind direction. In the stable conditions due to steady temperatures of the sea the horizontal **angle of dispersion** is between 1.5 and 3 degrees while the vertical one is between 0.3 and 1 degree. The former will affect cross-wind dispersion and the latter the rate at which drops fall back into the sea. However there is a further complication because of movements below and within clouds and by the effects of charge.

Required investment

A development programme has been planned to reduce technical uncertainties as rapidly as possible. These are mainly connected with spray generation dispersion and meteorological modeling of effects. Very few will remain after the expenditure of the first £5 million. It will need perhaps £25 million to complete research and development and £30 million for tooling before the returns begin. Depending on spray rates and distribution effectiveness it is possible that 500 spray vessels costing £1 million each with a life of 20 years could cancel the thermal effects of a one-year increase in world CO2.

The crucial political requirement is that albedo cooling should be included in the carbon-trading market which was set up before Lathams 's proposal was known to carbon-trading planners.

Potential returns

The carbon trading market works very much the like the Papal indulgences which so annoyed Martin Luther. It is intended to keep emissions at 5.2% below 1990 levels by requiring that people wanting to exceed that level should pay others to counteract the increase. Recent high and low spot values were €28.6 and €18.6 per tonne of CO2. A prediction for the total market for 2005 is €5 billion. The potential market for albedo control would be this amount minus removals by carbon sequestration times a factor for any increased perception of the dangers of global warming.

However the carbon trading markets were set up by people who were unaware of the potential of albedo control. Some renegotiation will be necessary if commercial investment is to fund it.

The prediction for 2020 is for an increase of atmospheric CO_2 by a factor of 1.7. At a cost of €20 per tonne this would represent an annual market of €3500 billion. The calculation is complicated because opinions about the cost of losing low-lying countries are subjective and the dangers of global warming are non-linear. For example, the amount of land flooded by rising sea levels will rise very sharply as levels increase. The frequency and severity of hurricanes rises abruptly for sea temperatures above 26.5 C. There are events such as release of methane from permafrost, loss of ice cover or changes in the thermo-haline circulation which will, in turn, trigger other rises. None of the non-linearities so far identified suggest any reduction in 'market value ' of reduced temperatures.

Albedo control will produce only a thermal effect and does nothing about the chemical effects of CO_2. However some extra CO_2 could be beneficial for crop production and this might to some degree compensate for the problems caused by increased acidity of the oceans. Albedo control would also be able to regulate temperature rises which are not connected with CO_2, such as variation in solar inputs.

Conclusions

Present efforts to prevent global warming are like moving the deck chairs to the side away from the iceberg hole in the hope of sinking more slowly.

Leading atmospheric physicists agree that albedo control by exploitation of the Twomey effect could allow double CO_2 with no temperature change **provided** that all the engineering problems of spray generation and distribution can be solved.

Spray distribution could be done from a fleet of some hundreds remotely-controlled wind-driven vessels.

The Flettner rotor is an attractive alternative to sails because of its high lift coefficients, easy control by computer and the convenience for housing spray plant and ejecting spray.

Some way must be found to include albedo cooling in the carbon trading market.

References

Anon. European Process Safety Centre. Atmospheric Dispersion. Institution of Chemical Engineers. Rugby 1999. (Translation from French of a report from 1995.)

Bower K, Choularton T, Latham J, Sahraei J, Salter S. Assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds. Journal of Atmospheric Science. 2005. (Accepted, in press).

Latham J. Control of global warming. Nature 347 pp 339-340 1990.

Latham, J. Amelioration of global warming by controlled enhancement of the albedo and longevity of low-level maritime clouds.Atmos. Sci.Letters. 2002doi:10.1006/Asle.2002.0048.

Mittal S. Kumar B. Flow past a rotating cylinder.
J. Fluid Mech. vol. 476, pp. 303-334. 2003.

Seufert W and Seufert S. Critics in a spin over Flettner 's ship New Scientist 10 March 1983 pp 656-659.

Twomey, S., 1977: Influence of pollution on the short-wave albedo of clouds. J.Atmos. Science., 34, 1149-1152.

Walton W H and Prewett WC. The Production of Sprays and Mists of Uniform Drop Size by Means of Spinning Disc Type Sprayers ".Proc. Phys. Soc. (London) B , 62, p. 341 (1949).