Roger Aines of Lawrence Livermore National Laboratory in California sees air capture playing a potential part. He and his colleagues are making an overview assessment of the strategy, and estimate that the quarter-gigatonne target could be met by, say, a thousand 250,000-tonne air-capture facilities requiring a total of 900,000 gigawatt-hours of energy per year. This is slightly more than the total electricity generated by the 104 nuclear power plants in the United States. If wind were to supply the power, the world would need something like 135,000 additional 1.5-megawatt turbines. That would approximately double the current global wind-power capacity.

Such a scenario is within the realm of possibility, but it demands an increase in energy production just at a time when we should be trying to break our energy addiction. For some, that's a critical problem. Every dollar spent on air capture instead of shifting to renewables is "a long-term loss to society", says Mark Jacobson of Stanford University in California. His concern is that researching a 'get out of jail free' card for climate change would provide an excuse to continue unabated emissions.

David Keith and his carbon-capture machine.

K. BENDIKTSEN, UNIV. CALGARY

That worry is voiced by many, but it is also dismissed by many. "For some people there's concern that if there's hope that air capture will work, it reduces the incentive to reduce emissions," says Pielke. "That makes as much sense as saying we shouldn't have open-heart surgery because it stops people from lowering their cholesterol. We need both."

No one argues that air capture is a cure-all. Eisenberger sees it as a necessary bridge to get us more painlessly to our goal of a renewable-energy economy. Despite the 'reasonable' price tag of air capture, it is still cheaper, and more sensible, to capture large-industry pollutants at source and to reduce energy use. "Air capture would be a back-stop technology to fill in the gap between what we can achieve and what our goals are," says Pielke.

"It is the most expensive climate-mitigation technology," agrees Zeman. "And that's a good thing. It has this role as the upper bound on solving the climate problem." No matter what we have to do to get the atmosphere settled, it won't cost more than this. ■

Nicola Jones is a commissioning editor for *Nature*'s Opinion section.

See also Editorial, page 1077, and www.nature.com/climatecrunch.

1. Pielke, R. A. Jr *Environmental Science & Policy* (in the press).
2. McKinsey & Company *Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve* (2009).
3. Keith, D. W., Ha-Duong, M. & Stolaroff, J. K. *Climatic Change* **74,** 17–45 (2005).

Great white hope

Geoengineering schemes, such as brightening clouds, are being talked about ever more widely. In the third of three features, **Oliver Morton** looks at how likely they are to work.

Something utterly insubstantial is rising above the rim of the beaker on the table. It looks like a white mist; it feels like nothing. Run your hand through it and you get no sense of warmth or cold. It leaves no moisture on the skin, no smell, no taste. It's just a whiteness. You can see that it would spur curiosity; that it might spur controversy is harder to imagine.

The mist is made up of droplets of water just a few micrometres across, thousands of times smaller than a raindrop. The man who set up this beaker as a demonstration, a nominally retired professor of engineering at the University of Edinburgh, UK, named Stephen Salter, thinks that ships designed to produce such mists could whiten the low layers of cloud that hang above the sea over large areas of the globe. Established theory predicts that such whitening, if achieved, could cool Earth significantly — a thousand such ships might cool it as much as decades of carbon dioxide emissions would warm it.

The beaker demonstration was part of a one-day meeting held at the University of Edinburgh in mid-March to look at how cloud whitening could move beyond the era of the tabletop. The meeting's agenda was vast, encompassing climate modelling, cloud physics, data from a field campaign studying clouds off the coast of Chile, the design of ships and the minutiae of the tiny nozzles needed to create such ultra-fine sprays. It ended up, as almost all such discussions of cooling the Earth do, heading off into questions of morality, politics and public perception.

The frequency of such meetings shows how this topic, known as geoengineering, is gaining, if not acceptance, at least an enhanced currency. For a number of the participants, this was their second day of geoengineering presentations that week — there had been an all-day discussion of the topic at the International Scientific Congress on Climate Change in Copenhagen two days before. The following week, some of the key players would be at it again, this time at a workshop organized by the US Defense Advanced Research Projects Agency in Stanford, California.

As yet, though, these discussions are, like Salter's mists, insubstantial. Very little funding is available for real research into whether ships are the best way to whiten clouds, or whether cloud whitening is really a workable way to cool the world. And that is cause for concern because there is a real possibility that such schemes won't work. "The most dangerous case is … when you think that geoengineering works and you're wrong," said David Keith of the University of Calgary in Canada while at the Copenhagen meeting.

Could a fine mist help to combat global warming?

R. GUSTHART

The worry that Keith and others share is that a growing interest in geoengineering tends to promote the belief that it is a plausible option, even though there is not enough research to back that up. And interest is undoubtedly growing, in ways that go well beyond the small number of scientists trundling from meeting to meeting. The American Meteorological Society in Washington DC is consulting with its membership about a policy statement on the subject, and Britain's Royal Society is preparing a report chaired by John Shepherd, an oceanographer at the University of Southampton, UK. John Holdren, science adviser to US President Barack Obama, says that the technology should be looked at on the basis that nothing should be taken off the table; the economist Nicholas Stern, author of the influential *Stern Review on the Economics of Climate Change*, says much the same in an interview on this week's *Nature* podcast.

The discussions in science and policy circles are typically and appropriately couched with caveats about the unknown feasibility and safety of such ideas and the much greater desirability of cutting emissions. Although Greenpeace International has not called for a ban on geoengineering research, David Santillo, a scientist with the organization, argued at the Copenhagen meeting that such a policy might ideally be the best position, so that no creeping faith in the possibility of a last-ditch alternative would ever undercut the need to reduce emissions.

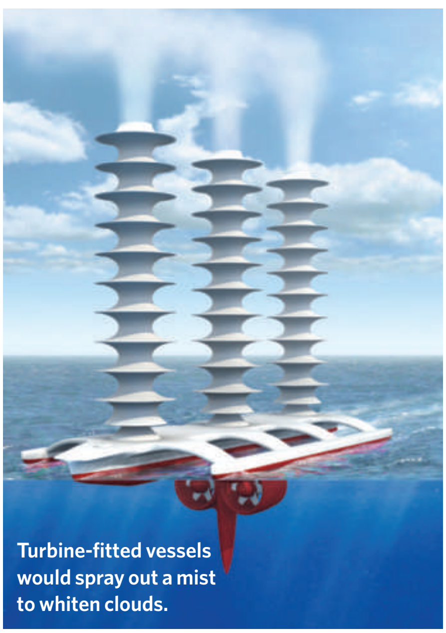
First, choose your wavelength

Geoengineering approaches can be divided into two categories, short-wave and long-wave. Short-wave approaches reduce the amount of energy entering Earth's system by increasing the amount of sunlight that bounces back out into space without being absorbed. Long-wave approaches help infrared radiation to escape from the atmosphere, usually by reducing the concentration of CO_2 — for example by turning biomass into charcoal and burying it, or by fertilizing plankton blooms. Both approaches have their proponents, but as Timothy Lenton and Naomi Vaughan of the University of East Anglia, in Norwich, UK, have shown, the amount of cooling that might be expected from long-wave schemes is substantially less than you can get from short-wave ones (T. M. Lenton and N. E. Vaughan *Atmos. Chem. Phys.* **9,** 2559–2608; 2009).

Short-wave schemes can be distinguished further by altitude. Sunlight can be reflected before it reaches the planet by some sort of shield in space. Or it can be turned away closer to home: by aerosol particles in the stratosphere; by clouds in the lower atmosphere; or by white objects on Earth's surface, such as painted buildings and roads. Lenton and Vaughan found that the last of those options — making the surface more reflective — would not be able to produce an effect large enough to counteract a doubling of CO_2. The first — 'sunshades in space' — could in principle counteract any warming effect that can be imagined. But it would require spacecraft vast in either size or number, a spectacularly ambitious and costly undertaking for a civilization that has no way of delivering 100-tonne payloads to the lowest of orbits.

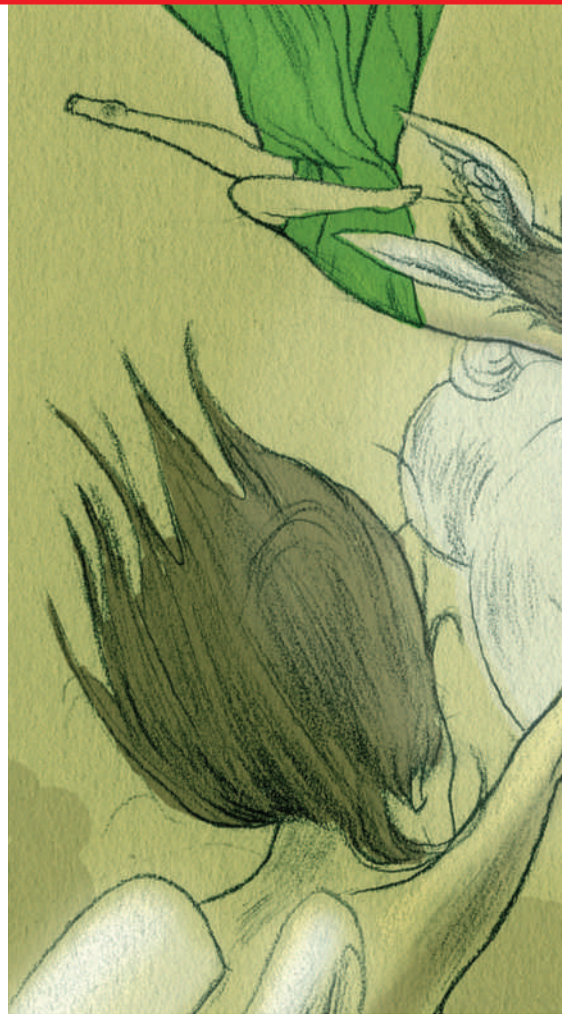
That leaves the stratosphere and the clouds. The stratosphere has received the bulk of geoengineering attention (see *Nature* **447,** 132–136; 2007), mainly because volcanic aerosols at that height have clearly cooled the globe, and because this type of cooling is amenable to the sort of global modelling that climate researchers are good at. But such an intervention raises numerous issues. Particles injected into the stratosphere might also catalyse chemical reactions that could deplete the ozone layer. And although they — or the raw materials to produce them — could be lifted that high in a number of ways, it could be hard to make such a system operational and potentially impossible to ensure that the particles remain at the right size. Furthermore, stratospheric aerosol particles have a lifetime of a couple of years — long enough to wreck whole growing seasons if their side effects included suppressing rainfall.

An attraction of the cloud-based approach is that it gets around some of those issues. It uses nothing more than seawater, it doesn't require things to be lifted tens of kilometres into the sky, it can be tested on a local or regional scale and it can be turned off instantaneously. The idea was first put forth in 1990, by John Latham, a British atmospheric scientist now based at the National Center for Atmospheric



Turbine-fitted vessels would spray out a mist to whiten clouds.

S. SALTER/J. MACNEILL



ILLUSTRATIONS BY J. BURTON

Research (NCAR) in Boulder, Colorado. For water vapour to form into clouds, the atmosphere needs to contain particles for the water vapour to condense on, called cloud condensation nuclei. Air that is well supplied with these nuclei will contain many small water droplets. In air that has a smaller number of nuclei, condensation will form fewer, larger drops. Clouds consisting of small droplets are more reflective than those with larger ones, and under some conditions they will also last longer. So if you were to inject condensation nuclei into clouds you would, other things being equal, make them brighter.

Some 25% of the world's oceans are covered with thin, low-lying layers of stratocumulus cloud. Make them brighter, Latham says, and you could cool the planet. So Salter has designed wind-powered ships that use underwater turbines to drive machinery to make the fine mist that can provide the necessary particles. Such ships, which would operate, in principle, without a crew, could seed clouds over the necessary swathes of ocean.

Phil Rasch, a climate modeller who until recently was a colleague of Latham's at NCAR and who is now at Pacific Northwest National Laboratory in Richland, Washington, has looked at how effective such brightening might be. By manipulating the number of cloud condensation nuclei in a global circulation model of the climate, Rasch found that seeding 25–50%

of the ocean with droplets of the right size could offset a greenhouse warming of 3 watts per square metre — the amount that might be expected from a doubling of CO_2. Running the model with doubled CO_2 showed that seeding could keep the average temperature where it is now, or in some scenarios actually diminish it. This might take hundreds or indeed thousands of ships, depending on their capacities. Salter, for one, thinks that such a fleet would be quite cheap. "Do not be put off by yachts for the rich, with diamond-encrusted lavatory seats. Check out fishing boats." He thinks that around a thousand \$2-million ships could do the trick.

But even though they are of the same order of magnitude, the cloud effect does not perfectly counter the greenhouse effect. Brighter clouds cool only during the day — and do it best in summer — whereas greenhouse warming is felt 24/7. This imbalance applies to short-wave geoengineering schemes that use stratospheric aerosols, too, and it means that the net effect seen in models that include both greenhouse warming and geoengineered cooling of this type would never be just the status quo ante. Crucially, patterns of precipitation, among other things, change. But the disparity would probably be much stronger in a cloud-brightening scheme that targets only the ocean than in a stratospheric veil that operates globally. A wide range of climate phenomena are driven by temperature differences between the oceans and the land, from sea breezes to monsoons. How they would be affected by cloud brightening is something no one can yet say with any confidence. Nor can they say what the implications might be for ocean currents — a topic that Rasch is actively pursuing.

Clouding the issue

Atmospheric scientists understand fairly well the process that creates and dissipates the clouds in question. But the relative weights of various processes and how they interact are still not understood — and those weights might be crucial to whether a cloud-seeding scheme could actually work, says Tom Choularton, who heads the cloud-research group that Latham started at the University of Manchester, UK, in the 1960s. Take, for instance, the role of convection in the marine boundary layer — the mixed layer of air that extends a few kilometres above the ocean surface. At night, convection mixes air from the bottom of the layer all the way to the top, lifting up moisture from the warm ocean to form clouds at the top of the layer. During the day, though, the clouds at the top of the layer bask in the sun, so the layer is heated from both the top and the bottom. This means that the whole-layer convection pattern can break down, with the upper part, including the clouds, 'decoupling' from the lower. The evaporation of drizzle beneath the cloud can cool the middle of the layer, exacerbating the effect. Decoupling would make it much harder to get condensation nuclei from the surface to the clouds in the first place.

> "Do not be put off by yachts for the rich. Check out fishing boats."
> — Stephen Salter

A linked concern, pointed out by Rob Wood of the University of Washington in Seattle, is that it is hard to gauge the effect of adding condensation nuclei on the clouds' lifetime. More cloud nuclei would be expected to make clouds persist by suppressing the growth of large droplets, which fall out of the cloud as precipitation. But suppressing precipitation might increase the vigour of the circulation in the upper part of the boundary layer. That could draw in dry air from above, leading to increased evaporation, which would thin and disrupt the cloud.

The approach that Latham and Salter have laid out relies on the creation of very small water droplets, which dry out to form little specks of sea salt on which the water vapour in the cloud will condense. These salt particles will attract more water vapour than the particles that currently dominate the aerosols over the open ocean, which tend to be ammonium sulphate created by chemical reactions in the atmosphere. If the salt particles outcompete the sulphate particles, the net effect on droplet number might be small

H. COE/NCAS/UNIV. MANCHESTER

Whitening the clouds that lie low over the ocean could help to cool the Earth.

or even negative, with bigger droplets forming.

To avoid this fate, the salt particles need to start off very small indeed. That makes designing the system to create the spray even more challenging. Salter has been told by various experts in industrial spraying that it would be simply impossible. He refuses to believe that, and the Edinburgh meeting saw vigorous debate between him and Armand Neukermans, a California-based innovator with a long track record of developing technology for, among other things, ink-jet printers, about ways to make very small droplets. They agreed that the smallest size feasible remains unclear — as does a great deal else associated with making such droplets day in day out, starting with unfiltered sea water, on a ship with no human crew.

"There's the potential to learn a lot more by intervening." —David Keith

VOCALS support

At every point in the Edinburgh meeting, and at every scale from the micrometre to the global, the need for further research shone through. Many of the participants had been involved in a project that might serve as a model for future studies. In late 2008, researchers from 30 institutions used a range of satellites, aircraft, research ships and land-based observations to study cloud processes off the coasts of Peru and Chile, as part of a project called VOCALS, which is a component of an even larger study called the Variability of the American Monsoon Systems (VAMOS) project. (VOCALS, on which Wood was the principal investigator, stands for the VAMOS Ocean-Cloud-Atmosphere-Land Study). The data they gathered should improve understanding of the interaction between clouds, drizzle and aerosols, and the degree to which aerosols both above and below the clouds affect their properties. Of particular interest were holes that form in the cloud layer as a result of local decoupling.

Daniel Rosenfeld of the Hebrew University in Jerusalem sees opportunity in such holes. He thinks that the aerosol concentrations will differ very little between a solid cloud bank and one filled with holes. In a poster at last December's meeting of the American Geophysical Union in San Francisco, he built on this idea to suggest that aerosol-producing ships might be able to convert a patchwork cloud layer into solid cloud quite easily. This already seems to happen sometimes in the smoky wakes of commercial ships. If it works, such a strategy would provide a much more powerful cooling effect than merely brightening clouds that are already there, giving Rosenfeld's approach remarkable leverage, he thinks, with a much smaller fleet needed. But as the more intense cooling has a more local effect, the equal-not-opposite mismatch between cooling and warming might be even more problematic.

For pretty much everyone at the Edinburgh meeting, the medium-term goal for research into cloud brightening seemed to be a VOCALS-type experiment in which droplet-making technologies and their effects are studied over hundreds of square kilometres. Even that would not resolve all the issues about the feasibility of such a scheme, and it can't be rushed into — more basic research needs to be done first, in terms of cloud modelling and nozzle making — but it would be a start. And such tests could have implications for climate research more broadly. As Keith pointed out at the meeting, "There's the potential to learn a lot more by intervening." Being able to experiment on clouds might reveal a great deal that climate scientists need to know, about what will happen in a warmer world even if geoengineering proves impossible, Choularton says.

However, as yet there is no funding for such efforts. Of everyone using the VOCALS data, only one PhD student is doing so with a specific geoengineering-oriented goal. And what concerns researchers is that things might stay that way. It is one thing to get people to talk about geoengineering — it is another to make it a serious research topic with significant funding. Indeed, if general discussion of the possibility leads to increased polarization and opposition — as it very well might — then it may become more difficult, not less, to do the work necessary to test the possibility.

Paradoxically, the intense debate over this topic could keep it alive and in the realm of possibility. At some point in the future, perhaps not too far away, society could be searching for a last-gasp response to global warming. The more that people talk about geoengineering, the more likely they will be to assume there is something solid in the idea. In fact, though, it may be as insubstantial as Salter's mist aspires to be. ■

Oliver Morton is *Nature*'s chief News and Features Editor.

Since the writing of this article, the author now participates in scientific research on the topic.

See also Editorial, page 1077, and www.nature.com/climatecrunch.