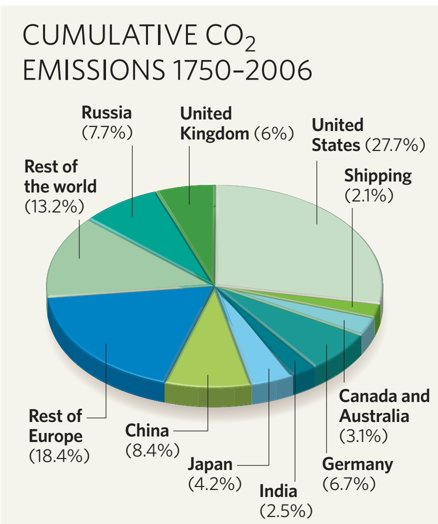
stabilizing at a particular level. So the climate never reaches equilibrium and the uncertainties about its long-term response do not matter as much. "If you assume a finite injection of carbon," says Allen, "you don't need to know the climate sensitivity, so this whole debate about the equilibrium response is moot."

Although the results of the studies might seem too daunting, they do offer a few rays of hope. Andrew Weaver, a modeller at the University of Victoria in British Columbia, Canada, says that in the new studies, what matters is how much pollution goes into the sky, not when it gets emitted. "This allows you some flexibility," he says. From a political perspective, the idea of a cap on total emissions "is a lot easier to get your head around" than a concentration target or, say, a 20% reduction below 1990 emission levels. A cap is like a budget. Once you use it up, there's nothing left to spend.

Unfortunately, the world is behaving as though it expects to be able to arrange a large overdraft. And researchers can only come up with so many ways of presenting the gravity of the carbon problem to the rest of the world. "At some point, you begin to throw your hands up. It's very frustrating," says Weaver, who pulls a reference from an ancient global crisis. "Climate scientists," he says, "have begun to feel like a bunch of Noahs — thousands of Noahs." ■



SOURCE: CARBON DIOXIDE INFORMATION ANALYSIS CENTER, OAK RIDGE NATIONAL LABORATORY

Richard Monastersky is a features editor with *Nature* in Washington DC.

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

1. Hansen, J. *et al. Open Atmos. Sci. J.* **2,** 217–231 (2008).
2. Calov, R. & Ganopolski, A. *Geophys. Res. Lett.* **32,** L21717 (2005).
3. Solomon, S., Plattner, G.-K., Knutti, R. & Friedlingstein, P. *Proc. Natl. Acad. Sci. USA* **106,** 1704–1709 (2009).
4. Lowe, J. *et al. Environ. Res. Lett.* **4,** 014012 (2009).

ILLUSTRATIONS BY J. BURTON

Sucking it up

It's simple to mop carbon dioxide out of the air, but it could cost a lot of money. In the second of three features on the carbon challenge, Nicola Jones talks with the scientists pursuing this strategy.

When Frank Zeman made a device to mop carbon dioxide out of the air of his laboratory at Columbia University in New York, it didn't look like a machine that could save the planet. Black tape held together plastic parts eaten away by lye; baking soda encrusted the outside. If someone walked behind the air intake (which looked like a grey hair dryer), their exhalations would interfere with the results. But the contraption worked.

Such a device, if scaled up and perfected, could be used to dial back Earth's greenhouse thermostat by taking CO_2 straight out of the sky. Although Zeman's fully functioning desktop device has not yet made it out of the lab, others have developed parts of bigger and more ambitious devices, some of which are heading for commercialization. All are imperfect, but they all work, and that undeniable fact is turning air capture from a 'what-if' pub discussion into a serious proposal.

"Nobody doubts it's technically feasible," says Zeman, now director of the Center for Metropolitan Sustainability at the New York Institute of Technology.

Increasingly it looks like air capture will be needed. Efforts to limit CO_2 emissions will need to be strengthened massively if they are to keep concentrations from reaching dangerous levels, so there may be little choice but to remove some of the CO_2 already in the air (see page 1091) or cool the planet in other ways (see page 1097). "Without having something that is carbon negative, the possibility of avoiding high levels of CO_2 is basically zero," says Peter Eisenberger, former director of the Lamont–Doherty Earth Observatory at Columbia University and co-founder of the air-capture company Global Thermostat.

In a recent analysis, Roger Pielke of the University of Colorado in Boulder put some numbers on the task ahead. Assuming a middle-range scenario projected by the Intergovernmental Panel on Climate Change (IPCC), humanity must somehow prevent itself from emitting (or must soak up) 650 gigatonnes of carbon by 2100 to keep concentrations under 450 parts per million (p.p.m.) at that point[1]. To put that in perspective, humans added about 9 Gt of carbon to the atmosphere last year.

THE CLIMATE CRUNCH

Economic studies suggest that some reductions could come affordably, or even at a profit, from fairly obvious places. Deeper cuts would require serious money. A report from the international consultancy McKinsey estimates that energy-efficiency measures, conversion to low-carbon energy sources, and forestry and agriculture management could — with serious effort — cut about 10 Gt of carbon emissions annually by 2030, for under US$300 per tonne. But it will be much harder and more expensive to get at any fraction of the remaining 9 Gt of annual emissions expected that year in a business-as-usual scenario[2]. Pielke is one of many beginning to wonder whether mopping up CO_2 with chemicals and machinery — a strategy with an ironically un-green image — might be part of the answer.

It could be an unbeatable idea. Sponging CO_2 from the air has a direct, immediate and measurable effect on the source of the

problem, avoiding the possible side effects of geoengineering. Air-capture devices can be sited anywhere, although preferably on cheap land with an untapped renewable energy supply and a geological reservoir that could serve as a dump for the captured gas. In principle, there is no limit to how much CO_2 you can extract: name an atmospheric concentration you'd like to end up with, and the technology can get you there.

To many in the 1990s, that cost seemed ridiculously high. In engineering circles, the dogma ran that the ease of extracting a gas was proportional to its concentration. At 0.04%, CO_2 in the atmosphere seemed exceedingly difficult; the effort and money needed to extract and store CO_2 from industrial flue stacks, where it can make up perhaps 10% of all gas, is already high, estimated by the IPCC to cost between \$70 and \$260 per tonne of carbon (see *Nature* **442,** 620–623; 2006). The assumption was that filtering CO_2 out of the atmosphere would be 250 times harder and vastly more expensive.

That assumption turns out to be wrong. The benefit of air capture is that it deals with a nearly infinite and relatively clean source, so there is no need to scrub out polluting gases before beginning and no need to take out every last bit of CO_2. Thermodynamically, the task proves to be about twice as hard as flue-stream capture[3]. Better still, the technology to make such devices is already available.

Although air capture has been ignored by the IPCC and sidelined by scientists, that is changing. Researchers in Canada, the United States and Switzerland have come up with plans, tested prototypes, filed patents and founded companies to pursue the idea.

Which technology will win out is yet to be seen. The Virgin Earth Challenge, launched by airline entrepreneur Richard Branson and former US vice-president Al Gore in February 2007, offers up to \$25 million for the first demonstrably viable commercial design to remove significant amounts of greenhouse gases from the atmosphere (the exact criteria are unclear). As yet the prize goes unclaimed.

The bare-bones chemistry of carbon capture is simple. The simplest thing to do is to expose air to a sorbent of lye (NaOH). This reacts with CO_2 to create a solution of sodium carbonate. It's so simple that Klaus Lackner, also of Columbia University, once helped his daughter to do it for a school science project. To get the carbon out of solution, a trick can be borrowed from the pulp and paper industry: when slaked lime ($Ca(OH)_2$) is added to the mix, particles of calcium carbonate settle out. Throw this into a kiln and you are rewarded with a pure stream of captured CO_2 and quicklime (CaO), from which the sorbent can be renewed.

Crude prototypes

This is how Zeman's desktop device worked, and also how David Keith of the University of Calgary in Alberta, Canada, is pursuing the problem. Keith built a large-scale machine a few years ago to see how much CO_2 could be sucked up in practice. He calls it the 'Russian tractor' technique — not especially high-tech, but proven to work. A prototype featured on the Discovery Channel in 2008 mopped up a few kilograms of carbon overnight.

Keith didn't build the second half of the scheme — the 900 °C kiln that spits out concentrated CO_2 — because that's already a known industrial process. It's also the energy-intensive and costly part. Nevertheless, he is setting up a company called Carbon Engineering, convinced the idea is worth pursuing, and is working to reduce costs.

Keith has chosen the most obvious approach to the problem but admits that others have "much more clever" schemes. That includes a material being developed by Lackner for the company Global Research Technologies, based in Tucson, Arizona, and funded by a \$5-million donation from the late billionaire Gary Comer. (Comer, founder of the Lands' End clothing-catalogue company, donated money to fight climate change after he sailed through the Northwest Passage in 2001 without being blocked by ice.) In April 2007, Global Research Technologies had its first demonstration of air capture with a prototype device. It was a success, widely lauded in the press, but it needed further work. For one thing, it just vented the captured carbon out the back. For another, it didn't behave as it was expected to. "When we closed the door on it, something was happening we didn't understand," says Lackner.

The device used a commercially available

A way to pay for capturing carbon dioxide

Around the world, some 5.5 million tonnes of carbon are used each year in dry ice or in compressed carbon dioxide to transport ice cream, flash-freeze meat, blast-clean engine blocks and carbonate drinks. The CO_2 purchased for that 'merchant market' can cost from US\$130 to \$1,100 per tonne of carbon.

Capturing CO_2 from the air is estimated to cost up to \$500 per tonne of carbon using today's technologies. If the aim was to bury the carbon underground and sell the deficit on the carbon-credit market, it would be hard to make a buck: carbon prices are currently €25 (US\$30) per tonne of carbon on the European trading market. But the \$1,100 per tonne price tag within the merchant market sector looks appealing to Klaus Lackner and the Global Research Technologies air-capture company.

Lackner foresees a world where the company's not-yet-built air-capture devices are carted around the United States from one willing customer to another. Because the CO_2 used by the merchant market ends up back in the air, this wouldn't do much to help the planet. But such a market could drive technological development and lower the price of air-capture devices, Lackner argues, until it becomes profitable to fight climate change.

An alternative profit-making scheme would be to turn captured CO_2 back into hydrocarbon fuel. Again, that's not ideal for reducing atmospheric CO_2, but it does create a carbon-neutral way of keeping fuel-guzzling cars on the road. **N.J.**

STONEHAVEN PRODUCTIONS

Klaus Lackner has imagined huge 'farms' featuring thousands of air-scrubbing devices that could soak up billions of tonnes of carbon from the atmosphere.

wet resin to mop up CO_2. When its designers analysed the results, however, they realized the material was better than they thought. Not only did it turn CO_2 into carbonate, but in a dry environment it would go a step further to bicarbonate. When they exposed the resin to water, the bicarbonate flipped back to carbonate, releasing CO_2 and water vapour. They didn't need a kiln — they just needed to expose their loaded resin to water in a relative vacuum, and then pressurize the result to condense the water out. "All you pay for is making the vacuum, pumping and pressurizing," says Lackner.

Others argue that kiln-temperature heat isn't necessarily a problem. In Zurich, Aldo Steinfeld and colleagues at the Swiss Federal Institute of Technology are using the Sun-tracking mirrors used by solar-power plants to heat up their air-capture reactor to 800 °C. They have a fully functioning lab model, and hope to have a larger field prototype within a few years to hand to an industrial partner.

Eisenberger, on the other hand, needs only low temperatures — under 100 °C, achievable using waste heat from power plants or cement factories — to run his system. Eisenberger's company Global Thermostat, which was founded in 2006 with Graciela Chichilnisky, an economist at Columbia University, is waiting for venture-capital funding to make a prototype, which could come as early as this autumn.

Eisenberger imagines a future in which air-capture devices start to be deployed by 2015; by 2020, half of new power generators are matched with air capture, and by 2040, some 9 Gt of carbon is being pulled from the air per year, to a total of 650 Gt by 2100 — the amount that Pielke also estimated would be needed. (Coincidentally, that total roughly matches the IPCC's estimate of the Earth's geological capacity to act as a garbage dump for buried gas). This whole operation could be accomplished by, say, 35,000 facilities that each took a quarter of a million tonnes of carbon per year out of the air. The combined footprint of this global operation would total less than 300 square kilometres — a fraction of the size of London.

"It is the most expensive climate-mitigation technology. And that's a good thing."
— Frank Zeman

Because Eisenberger assumes the world will also make substantial cuts in emissions over the same period, his air-capture scenario would return atmospheric concentrations to 380 p.p.m. of CO_2 by 2100, and they would continue to decline thereafter. The price? About $60 trillion for the air capture, or roughly $660 billion per year. That's on the same scale as the US economic stimulus package against the current recession, but every year for a century.

The price is the hardest thing to estimate, since no one has yet built a full-scale device. When Lackner first put out figures of about $100 per tonne of carbon in 2006, many saw it as massively over-optimistic — some joked that the real price was one mysterious 'Lackner' per tonne, given the apparently magical capacities of his material, the identity of which was kept under wraps for commercial reasons at the time. Today, Eisenberger's estimate is slightly cheaper still.

Cost competitive

At the other end of the scale, Keith has estimated it might cost $500 per tonne of carbon using today's technologies. That would rack up a bill of $325 trillion to soak up 650 Gt of carbon, but Pielke notes that such a price tag would still only be 2.7% of global economic output by 2100. That compares favourably with price estimates of the IPCC (−1 to 5% of global economic output) and economist Nicholas Stern (−2 to 4%) for stabilizing air concentrations at 450 p.p.m. without air capture.

"We should be looking into it, at least," Pielke concludes. To put the cost issue in perspective, he notes, if all the emissions from US cars were sucked up by air capture using today's technology, and the cost tagged onto the price of petrol, motorists in the United States would still have one of the lowest pump prices in the world.

Many air-capture enthusiasts talk about countering something on the scale of global aircraft emissions, projected to reach about 0.25 Gt of carbon per year by 2030. (Technology can reduce carbon emissions from power plants and cars, but it is difficult to reduce such emissions from planes.) This is where

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 CLIMATE CRUNCH

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.

Could a fine mist help to combat global warming?

R. GUSTHART

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.

The worry that Keith and others share is that a growing interest in geoengineering

Editor to quit over hoax open-access paper

The editor-in-chief of an open-access journal is to resign after claiming that its publisher, Bentham Science Publishing, accepted a hoax article without his knowledge.

Bambang Parmanto, an information scientist at the University of Pittsburgh, Pennsylvania, and editor-in-chief of *The Open Information Science Journal*, said he had not seen the computer-generated manuscript, accepted by Bentham on 3 June.

The fake paper was submitted by Philip Davis, a graduate student in communication sciences at Cornell University in Ithaca, New York, and Kent Anderson, an executive director at *The New England Journal of Medicine*. Davis says he wanted to test if the publisher would "accept a completely nonsensical manuscript if the authors were willing to pay". He retracted the paper after being notified that it had been accepted, and that he should pay US$800 to Bentham's subscription department.

Mahmood Alam, director of publications at Bentham Science Publishing, told *Nature* that "submission of fake manuscripts is a totally unethical activity and must be condemned", adding that "a rigorous peer-review process takes place for all articles that are submitted to us for publication".

For a longer version of this story, see http://tinyurl.com/lrx6m6

FDA gains the power to regulate tobacco products

L. JACK/CONTOUR

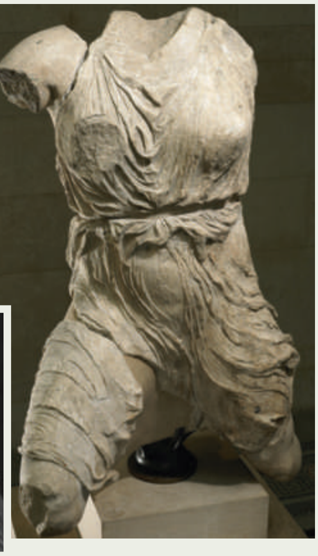
Obama in his youth.

The US Food and Drug Administration (FDA) will get the power to regulate tobacco for the first time in its 103-year history under legislation passed by Congress last week. President Barack Obama, himself a sometime smoker (see picture), has promised to sign the bill into law.

Passed by substantial majorities in both the House and the Senate, the Family Smoking Prevention and Tobacco Control Act requires that new tobacco products win pre-market approval from the FDA.

The bill bars the FDA from banning nicotine, but it gives the agency standard-setting authority that could lower nicotine levels in tobacco products. It constrains advertising, requires large warning labels on packaging and levies user fees paid by the industry to help finance FDA regulation. The fees will total $235 million in 2010.

Infrared scan reveals colourful past of the Parthenon



BRITISH MUSEUM

Conservation scientists at the British Museum in London have found the first evidence of coloured pigments on sculptures from the Acropolis in Athens. The figures formed part of the decoration on the Parthenon temple, and were taken from Greece by Lord Elgin in the early 1800s.

Ancient Greeks and Romans normally painted their sculptures, and traces of the pigments tend to survive on the objects to this day. But no hints of paint had been found on the Parthenon sculptures despite detailed studies — including an analysis in the 1830s by English physicist Michael Faraday.

The researchers revealed the presence of a pigment known as Egyptian blue on the belt of the goddess Iris (pictured). They used a portable detector to beam red light onto the surface and capture the infrared light emitted by the luminescent pigment particles (inset).

For a longer version of this story, see http://tinyurl.com/m24ylw

Japan's lunar orbiter ends mission with crash landing

The Japanese space agency's KAGUYA lunar orbiter ended its 21-month mission with a planned crash into the Moon on 10 June.

Formally known as SELENE (Selenological and Engineering Explorer), the mission was launched in September 2007. The orbiter gathered detailed geological information about the Moon, mapping its gravitational field and taking high-definition video images.

As *Nature* went to press, NASA's Lunar Reconnaissance Orbiter was scheduled to launch on 18 June. Together with India's Chandrayaan-1 spacecraft, which launched in October 2008, it will attempt to spot water ice at the Moon's poles (see *Nature* 459, 758–759; 2009).

Artefact raiders charged after undercover operation

A two-year federal investigation of widespread Native American grave robbing and artefact theft in the Four Corners region of the United States culminated in charges against 24 people last week.

The arrested individuals, from Utah, Colorado and New Mexico, were arraigned in the federal court on 10 and 11 June for multiple felony indictments for trade in 256 artefacts with a total value of more than US$335,000. Purloined items included pottery, baskets, sandals and necklaces taken from excavations on federal lands.

An undercover agent purchased the looted artefacts from, among others, a high-school teacher and an honoured archaeological-tourism promoter. One man — James Redd, a physician from Blanding, Utah — committed suicide on 11 June, authorities say, the day after he and his wife were charged with artefact theft.

US revives FutureGen 'clean' coal plant

The US Department of Energy (DOE) has announced plans to revive FutureGen, a commercial-scale coal-fired power plant in Mattoon, Illinois, that would capture carbon dioxide emissions and sequester them underground.

Under George W. Bush's administration, the DOE pulled the plug on the flagship 'clean' coal technology programme in January 2008, citing a dispute with industry partners over the US$1.8-billion price tag (see *Nature* 451, 612–613; 2008).

Energy secretary Steven Chu revived FutureGen on 12 June, announcing an agreement to restart the negotiations, update the cost estimate and begin preliminary design activities. The DOE and FutureGen industry partners hope to make a final decision on whether to go ahead with the project early in 2010.

Corrections

The News Feature 'Sucking it up' (*Nature* **458,** 1094–1097; 2009) incorrectly stated that Global Thermostat is waiting for venture-capital funding to build a prototype for the capture of CO_2 from the air. It already has sufficient funding in place.

The News story 'Funding struggle for mercury monitoring' (*Nature* **459,** 620–621; 2009) erroneously located Changbai Mountain in Taiwan. It is in northeastern China.

In the News Feature 'Nascence man' (*Nature* **459,** 316–319; 2009), the picture of the Lost City on page 318 should have been credited to D. S. Kelley.