ILLUSTRATIONS BY J. BURTON

A BURDEN BEYOND BEARING

The climate situation may be even worse than you think. In the first of three features, **Richard Monastersky** looks at evidence that keeping carbon dioxide beneath dangerous levels is tougher than previously thought.

In 2007, environmental writer Bill McKibben approached climate scientist James Hansen and asked him what atmospheric concentration of carbon dioxide could be considered safe. Hansen's reaction: "I don't know, but I'll get back to you."

After he had mulled it over, Hansen started to suspect that he and many other scientists had underestimated the long-term effects of greenhouse warming. Atmospheric concentration of CO_2 at the time was rising past 382 parts per million (p.p.m.), a full 100 ticks above its pre-industrial level. Most researchers, including Hansen, had been focusing on 450 p.p.m. as a target that would avoid, in the resonant and legally binding formulation of the United Nations Framework Convention on Climate Change, "dangerous climate change". McKibben was aware of this: he was thinking of forming an organization called 450.org to call attention to the number, and his question to Hansen was by way of due diligence.

As he thought about McKibben's question, Hansen, who runs NASA's Goddard Institute for Space Studies in New York, began to wonder if 450 p.p.m. was too high. Having spent

aware that in some respects the real world was outstripping them. Arctic sea ice was reaching record lows; many of Greenland's glaciers were retreating; the tropics were expanding. "What was clear was that climate models are our weakest tool, in that you can't trust their sensitivity in any of these key areas," he says. Those warning signs — and his studies of past climate change — led Hansen to conclude that only by pulling CO_2 concentrations down below today's value could humanity avert serious problems. He came back to McKibben with not 450 but 350. In 2008, he published a paper spelling out his rationale for that target[1].

The difference between 350 and 450 is not just one of degree. It's one of direction. A CO_2 concentration of 450 p.p.m. awaits the world at some point in the future that might conceivably, though with difficulty, be averted. But 350 p.p.m. can be seen only in the rear-view mirror. Hansen believes that CO_2 levels already exceed those that would provide long-term safety, and the world needs not just to stop but to reverse course. Although his view is far from universal, a growing number of sci-

greater than had previously been thought.

Several recent studies, for example, indicate that it may be exceedingly difficult to cool the climate down from any eventual peak or plateau, no matter what CO_2 concentration is chosen as a target by the international community. And by looking at the problem in a new sort of way — by tallying the total amount of carbon injected into the atmosphere across human history — two papers in this issue of *Nature* reveal how close the world has come to the danger point (pages 1158 and 1163). "It's tougher than people have appreciated. We have less room to manoeuvre," says Malte Meinshausen, an author of one of the papers and a senior researcher at the Potsdam Institute for Climate Impact Research in Germany.

Mr Greenhouse

Hansen has a long history of stirring up controversy with gloomy climate prognostications. Often, they turn out to be right. In 1988, he told the US Congress that the recent warming of Earth's surface was very unusual and it was time to point a finger at the cause. Hansen said it was his opinion that "the greenhouse effect has been detected and it is changing our statement, but the Earth continued to heat up and the rest of the scientific community eventually concurred with his assessment. He also used models to predict the amount of subsequent cooling to be expected from the eruption of Mount Pinatubo in 1991. That did much to convince people of the reliability of such models and of climate theory.

The model simulations Hansen and others worked on in the 1970s and 1980s had a profound effect on both climate scientists and politicians. When nations started exploring policies to curb CO_2 emissions, the target most discussed was 550 p.p.m., in large part simply because that was what the modellers had experience with: in early studies of the greenhouse future, researchers had sought to get a sense of the scale of possible change by simulating what would happen if the atmosphere held 550 p.p.m., roughly twice the pre-industrial level of CO_2 in the air.

"When you say we have to get to 350, you have to phase down CO_2 emissions in the next few decades." — James Hansen

Those studies showed a 550-p.p.m. world as warming quite a lot. In 1979, a panel of the US National Academy of Sciences led by Jule Charney, a prominent weather and climate researcher, estimated it would be 1.5 to 4.5 °C hotter. That estimate for what has become known as 'climate sensitivity' has stayed remarkably solid ever since: the most recent report of the Intergovernmental Panel on Climate Change pegged the sensitivity as being between 2 and 4.5 °C, while adding that higher values could not be excluded.

Although early policy discussions focused on the 550 p.p.m. mark, researchers and politicians soon concluded that such warming would be too much. In 1996, the European Union declared that "global average temperatures should not exceed 2 °C above pre-industrial level and that therefore concentration levels lower than 550 p.p.m. CO_2 should guide global limitation and reduction efforts". Over the following decade, 450 p.p.m. became increasingly cited as a level to aim for, because some studies associated that concentration with 2 °C of warming.

In their 2008 paper, Hansen and his colleagues offer a number of reasons for arguing that even 450 p.p.m. is too high. The most important are observational: rapid changes in the Arctic and elsewhere have demonstrated that the globe is more sensitive to even today's levels of greenhouse gases than climate models have predicted. Others depend

is defined. The standard approach, going back to Charney's formulation, comes from models that allow fast-reacting components of climate to change but hold constant other, slower factors, such as forests and ice sheets. Yet evidence from the past shows that such slow players are acutely sensitive to varying levels of CO_2 — and are not so slow. By analysing how temperature and greenhouse-gas concentrations actually correlate over the past 500,000 years, as ice sheets have waxed and waned, Hansen and his colleagues find that the true climate sensitivity is 6 °C.

Going even further back, the team argues there is evidence for a tipping point in the greenhouse. Some 50 million years ago, CO_2 concentrations were many times today's levels and Antarctica was ice-free. Concentrations declined slowly and crossed a crucial threshold 35 million years ago when the globe was cool enough for an ice sheet to start growing on Antarctica. Through a series of extrapolations, the researchers estimate that the threshold level was between 550 and 350 p.p.m. To avoid any risk of recrossing that threshold and losing Antarctica's ice, best keep at or below the bottom of that range: 350 p.p.m.

Hansen's arguments do not convince everyone. Stefan Rahmstorf of the Potsdam Institute says that there are important distinctions between melting and forming an ice sheet, and the two processes might occur at different greenhouse-gas concentrations. In fact, a 2005

K. DAVISON/GREENPEACE

modelling study conducted at Potsdam suggests that during a simulated ice age, the amount of warming needed to melt the North American ice sheet is consistently greater than the amount of cooling needed to grow it[2]. "You have a different threshold for the ice sheets coming and the ice sheets going," says Rahmstorf.

Hansen, though, sticks with the new low figure. He argues that realizing the world is already in dangerous climatic territory "completely changes the story. When you say 450 or 550, you're talking about what rates of growth you are going to allow. When you say we have to get to 350, that means you have to phase down CO_2 emissions in the next few decades."

Peak problems

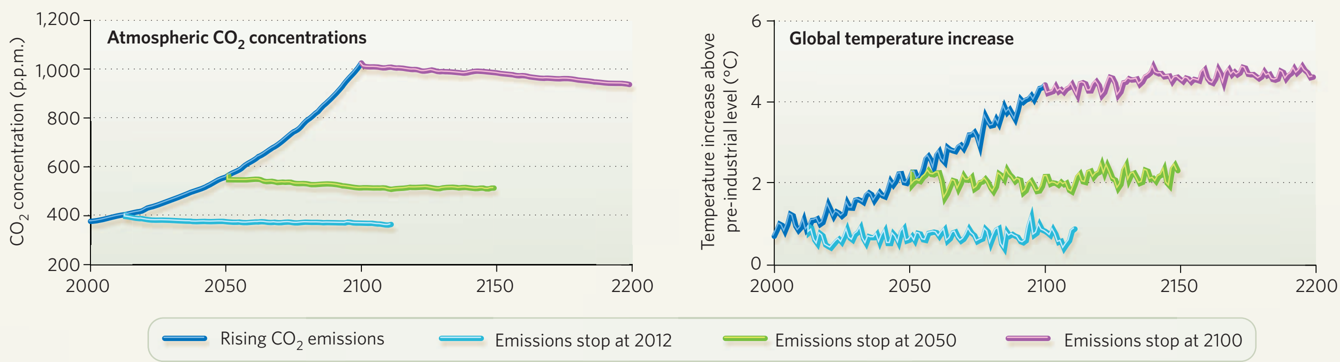
So how easy would it be to get back to 350 p.p.m.? Most scientists have assumed that it would not take that long to pull down CO_2 levels if humanity went cold turkey and cut off all emissions, says Susan Solomon of the National Oceanic and Atmospheric Administration in Boulder, Colorado. "I've done a little informal poll of colleagues," she says. "It was interesting, the number of smart, knowledgeable people who said if we stop emitting, things will go back maybe in 100 years, 200 tops. But they're not correct. And I didn't believe it would be so long either."

Solomon changed her mind because of a study in which she and her colleagues used what's known as an Earth-system model of intermediate complexity — an EMIC. Although not as detailed as general circulation models, which divide the atmosphere and ocean into millions of cells, EMICs have the advantage of requiring less computing and so can run simulations lasting many centuries. They are also useful because they represent Earth's carbon cycle — the natural movements of carbon between the atmosphere, the biosphere and the oceans. Using an EMIC developed by the University of Berne in Switzerland, Solomon and her colleagues tested what would happen if CO_2 emissions immediately ceased after concentrations peaked at various values, starting with 450 p.p.m. (ref. 3). What they found surprised them. CO_2 levels subsided so slowly that they remained substantially above pre-industrial levels 1,000 years into the future. Global temperatures also stayed up, and had declined only slightly from their peak by the year 3000. In fact the simulations ended before temperatures dropped anywhere close to their starting point.

According to Solomon, the simulated

THE LONG ROAD HOME

A complex computer model shows how Earth might respond if carbon dioxide emissions from humans stopped instantly at various points in the future.



SOURCE: LOWE, J. ET AL. ENVIRON. RES. LETT. **4,** 014012 (2009).

two factors. Natural sinks are only able to take up a fraction of the CO_2 in the atmosphere, so roughly 20% of the emitted gas will stay in the air for at least a millennium, ensuring that it continues to warm the globe long after emissions are cut off. The thermal inertia of the oceans also plays a part: the large mass of ocean water on the planet is delaying the rate of climate warming today because most of it is lagging behind the changes in surface temperature. Once it has warmed it will retard the Earth's cooling after emissions cease.

Slow recovery

Experiments conducted with a more complex model actually make the picture look worse. In a paper this year, Jason Lowe, head of mitigation advice at the UK Met Office, and his colleagues described a study using a general circulation model at the Met Office's Hadley Centre in Exeter, UK, coupled to a carbon-cycle model[4]. He found that after emissions were curtailed, temperatures remained elevated at least to the end of the simulation, which went on 100 years past the cut-off. In fact, if CO_2 concentrations reached 550 p.p.m. or higher before the emissions stopped, temperatures actually increased for at least a century (see graphs above). He would like to see other groups run similar experiments with their own general circulation models.

The take-home message from his and other studies, Lowe says, is this: "If you do end up somewhere you don't want to be, it's probably going to take you a long time to get back to lower temperature levels." Lowe is now looking at how long such warming would last and what kind of trouble it might get the world into by, say, melting the Greenland ice sheet.

Because it will apparently take so long for the climate to recover from excessive warming, researchers are now looking at new strategies

approach is to stop thinking about the levels at which CO_2 might be stabilized and instead concentrate on something simpler: the sheer amount of CO_2 that can be emitted in total.

In this issue of *Nature*, Meinshausen and his colleagues present results from a coupled climate–carbon cycle model that explores the effects of different emission pathways for CO_2 and the other major greenhouse gases (page 1158). For the period 2000 to 2050, they find that the world would have to limit emissions of all greenhouse gases to the equivalent of 400 gigatonnes of carbon in order to stand a 75% chance of avoiding more than 2 °C of warming. Other greenhouse gases, such as methane and nitrous oxide, are expected to produce as much warming as 125 gigatonnes of carbon in the form of CO_2 would; that means emissions of CO_2 itself over the half-century have to add up to less than 275 gigatonnes of carbon. That's an extremely difficult target, admits Meinshausen, considering that emissions over the past nine years have used up almost a third of that allowance already. "Our remaining emission budget is so small," he says. "If we want to have a smooth landing and to decrease emissions in a smooth way, our options are essentially exhausted. We have to bend down our emissions by 2020."

"If we want to have a smooth landing, our options are essentially exhausted." —
Malte Meinshausen

Also in this issue, Myles Allen of the University of Oxford, Meinshausen and their colleagues describe how they ran a series of simulations using a simple combination of climate and carbon-cycle models (page 1163). They find that if humankind could limit all CO_2 emissions from fossil fuels and changes in land use to 1 trillion tons of carbon in total, there would be a good chance that the climate would not warm more than 2 °C above its pre-

tons has already been spewed into the atmosphere, and emissions now average about 9 billion tons a year and rising, the trillion-ton limit would allow the world to follow its current trend for less than 40 more years before giving up carbon emission for good, all at once.

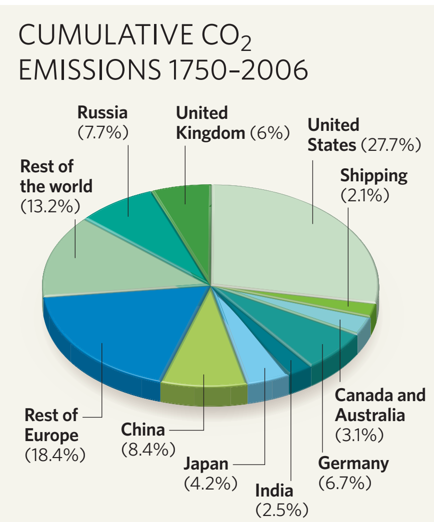
One way of looking at that challenge is put forward by Hansen. Go ahead and burn all the remaining oil and gas in conventional reserves, he says, and at the same time concentrate all efforts on quickly phasing out coal — or capturing and storing the emissions associated with it. If nations can cut off coal use by 2030 and avoid tapping unconventional fossil fuels, such as tar sands and methane hydrates, the world could limit future CO_2 emissions to 400 gigatonnes of carbon.

Other studies using this total-carbon-emitted approach are now appearing; a couple were presented at the International Congress on Climate Change held in Copenhagen in April. Although differing in details, they come to broadly similar conclusions. Allen says a total limit for carbon emissions, which he calls cumulative warming commitment, is a much more robust figure than a stabilization concentration of CO_2 in the atmosphere.

The problem with looking for a stabilization concentration is that one must first know the globe's long-term response — its 'equilibrium climate sensitivity' — to calculate how much the planet will eventually warm for a given concentration. Estimates of what that equilibrium climate sensitivity might be are shaky, and hence so are forecasts based on it. A focus on total carbon emissions rather than concentrations, however, wipes away that problem because it demands that concentrations go up 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." ■

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

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

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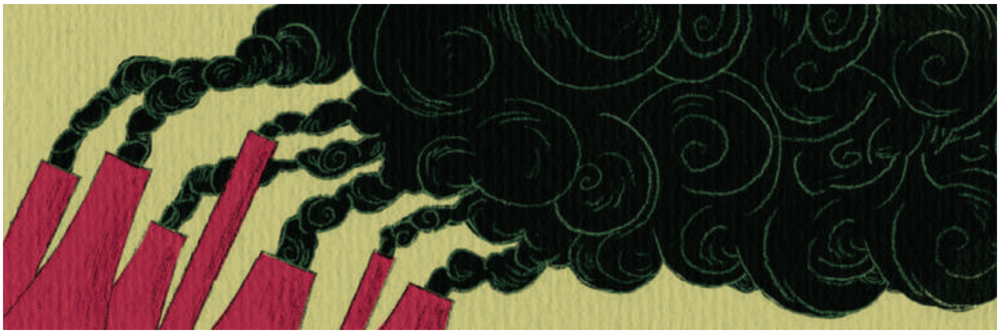

ILLUSTRATIONS BY J. BURTON

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

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