nature REPORTS climate change
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Avoiding the worst
Idealized emissions

HOW WILL THE PLANET RESPOND?
Tackling a sensitive subject

CLEAN DEVELOPMENT MECHANISM
Crunch time for carbon credits

nature REPORTS climate change
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SUFFICIENT CERTAINTY

Many argue that emissions targets should be the lynchpin of a global climate deal, but other than the goal of 'avoiding dangerous climate change', there is little agreement on what exactly we should be aiming for. The US delegation offered hope of progress at the first round of UN climate talks in Bonn, Germany, last month, where they committed to 'make up for lost time'. But this was quickly eclipsed by disagreements over how far and fast countries could go in reducing their emissions.

Much of the niggling over numbers can be put down to political wrangling, but there remains the issue of how exactly temperatures will rise with emissions. While the best estimates suggest this is 3 °C for a doubling of atmospheric CO_2 concentrations, it could be as high as 6 °C or more (see page 59). This calls into question whether even the most stringent mitigation scenarios being proposed for the upcoming negotiations in Copenhagen truly represent an acceptable attempt to avert the risk of dangerous climate change.

Though the European Union defines warming of more than 2 °C above pre-industrial temperatures as unacceptable, others such as NASA's James Hansen argue this should be 1.5 °C unless we are willing to suffer serious impacts. So should we aim to stabilize atmospheric CO_2 concentrations below 450 parts per million, as advised by economist Nicolas Stern in his latest book (see page 62) or at 350 parts per million, as recommended by Hansen?

And how would either translate into near- and long-term emissions targets? Would targets alone even be sufficient? Perhaps not, unless they are set within the context of an overall carbon budget, argue Myles Allen of Oxford University and others in this issue (see page 56). Their latest research suggests that to keep warming below 2 °C, we will need to limit cumulative CO_2 emissions to 1 trillion tonnes — twice that emitted since the pre-industrial era — as well as having shorter-term targets that require imminent political action.

If negotiators in Copenhagen agreed to such a strategy, it would be commendable and would undoubtedly bring us closer to limiting peak warming. But as with targets, carbon budgets are subject to uncertainty, and the warming from 1 trillion tonnes of carbon could be much larger than anticipated.

With just seven months to go — and only a few weeks of official meetings left — until the deadline to agree a successor to the Kyoto Protocol, now more than ever policymakers need scientific advice on climate change. On a policy-relevant timescale, the question of how sensitive the climate system is to greenhouse gases is likely to remain unanswered.

But absolute certainty is not a prerequisite for action. Dangerous climate change is going to be hard to avoid, and strong action taken in Copenhagen can only bring us closer to achieving that common goal.

OLIVE HEFFERNAN, EDITOR

Published online: 5 May 2009
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RESEARCH HIGHLIGHTS

COMMENTARY

FEATURE

BOOKS & ARTS

MARKET WATCH

The cover image is adapted from a figure by Myles Allen and co-authors on page 56 that shows various CO_2 emission paths each consistent with total cumulative emissions of 1 trillion tonnes of carbon.

Cover design by Karen Moore

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EARTH SCIENCE

Marsh attacks


KAREN MCKEE / US GEOLOGICAL SURVEY

Proc. Natl Acad. Sci. USA
doi:10.1073/pnas.0807695106 (2009)
J. Ecology **97**, 67–77 (2009)

Climatic warming by greenhouse gases is causing sea levels to rise, but two new studies find that elevated CO_2 might also help protect coastal marshes from going under. Sea level rise will destroy a marsh only if it outpaces the build-up of land, and CO_2 can encourage plant growth that swells the soil.

Patrick Megonigal of the Smithsonian Environmental Research Center in Edgewater, Maryland, and colleagues studied how fast soils gained elevation under increased CO_2 by exposing plots in a Chesapeake Bay wetland to concentrations of the greenhouse gas that were raised by 340 parts per million above ambient levels over two years. Whereas control plots lost 0.9 millimetres per year on average, the high-CO_2 plots gained 3 millimetres per year, driven by the amplified growth of plant roots, which added volume and mass to the soil. The boost was diminished, however, if nitrogen was added to the plots, a likely effect of pollution from expanding cities and fertilizer use.

In a companion study, Julia Cherry of the University of Alabama and co-workers transferred plots of marsh to the lab, where they mimicked the effect of an encroaching ocean. They found that high CO_2 stimulated plant growth and land build-up even when marshes were flooded with saltwater.

Anna Barnett

CLIMATE PREDICTION

Top models


© ISTOCKPHOTO / BLOODSTONE

Geophys. Res. Lett. **36,** L06710 (2009)

When it comes to simulating temperatures in specific regions, some global climate models are more skilful than others. For Australia, new research finds, those that reproduce past regional temperatures best also consistently project smaller increases in extreme temperatures in the future, relative to other models.

Sarah Perkins and colleagues at the University of New South Wales in Sydney tested nine global climate models for their skill in replicating past climate, by comparing their simulations of temperature extremes in Australia from 1981 to 2000 with observations. For each region of the continent, they picked the three models that performed best. This select group of models shows that if greenhouse gas emissions continue to grow, the very hottest days of 2081–2100 — the kind of scorchers that occur once every 20 years on average — will be 2 °C hotter than a century beforehand almost everywhere, and 5–7 °C hotter in the hardest-hit places. But if all models are included, peak temperature over most of the continent shoots up to 3–5 °C higher than a century ago.

The authors conclude that focusing on the best-performing models for a given region significantly changes climate projections. Since Australia includes both temperate and tropical climates, this effect could be widespread around the globe.

Anna Barnett

EARTH SCIENCE

Clear-cut carbon

Glob. Biogeochem. Cycles
doi:10.1029/2007GB003176 (in the press)

While re-growing, razed forests may sequester enough CO_2 to offset a substantial amount of the carbon lost to logging and other land-use change, a new model shows. Through practices such as clearing forests and cultivating cropland, humans have altered 42–68 per cent of the Earth's surface and added over a hundred billion tonnes of carbon dioxide to the atmosphere.


© ISTOCKPHOTO / LUOMAN

Now Elena Shevliakova of Princeton University, New Jersey, and colleagues provide the first global estimate of how much of the CO_2 emitted from land has been offset by re-growth, using a model of CO_2 sources and sinks in terrestrial ecosystems. To cover a range of possible land-use changes that may have taken place, they used four different scenarios. They found that even extensive human interference caused the net loss of only 1.1–1.3 billion tonnes of carbon per year in the 1990s — about half of previous estimates. One factor that may explain this, they say, is the 0.35–0.6 billion tonnes of carbon absorbed annually by plants growing back after disturbance, mostly in tropical forests.

The researchers suggest that replenishing of forests could be one of the 'missing' sinks that scientists have been seeking to help them balance the global carbon budget.

Anna Armstrong

BIODIVERSITY AND ECOLOGY

Sustaining sanctuary


© ISTOCKPHOTO / KROPA

Ecology Lett. **12,** 420–431 (2009)

As the climate changes, conservation areas will probably lose some species they were originally designed to protect, but overall they could still provide an important buffer against biodiversity loss. A new study finds that a network of important bird sites across sub-Saharan Africa should continue to afford protection to more than 88 per cent of the region's endangered inhabitants, despite anticipated changes in climate.

David Hole, of Durham University, UK, and colleagues examined the resilience of the sub-Saharan network, which holds 1,608 bird species, to a moderate emissions scenario over three time periods.

Community turnover — a measure of the change in species composition — increased throughout the twenty-first century, and reached an average of 26 per cent by 2085. But biodiversity fared well across the network, with, on average, 74–80 per cent of current bird species persisting in protected areas through to 2100. Of 815 species of conservation concern, 714–746 retained suitable habitat as the climate changed. Only seven or eight of the priority species lost climatically suitable habitat within the network by the end of the century.

Certain areas, such as the tropical highlands and the Namib-Karoo deserts, were particularly susceptible to species loss, however, and could lose up to 63 per cent of their priority bird species by 2100.

Anna Armstrong

CLIMATE IMPACTS

High and dry

US BUREAU OF RECLAMATION

Proc. Natl Acad. Sci. USA doi:10.1073/pnas.0812762106 (2009)

Millions of residents in Mexico and the southwestern United States who rely on the Colorado River for their water supplies may be left high and dry by the middle of the century. If temperatures continue to rise in the region, as anticipated, less runoff will mean that by 2050 the river will be unable to deliver the required water almost 60 to 90 per cent of the time.

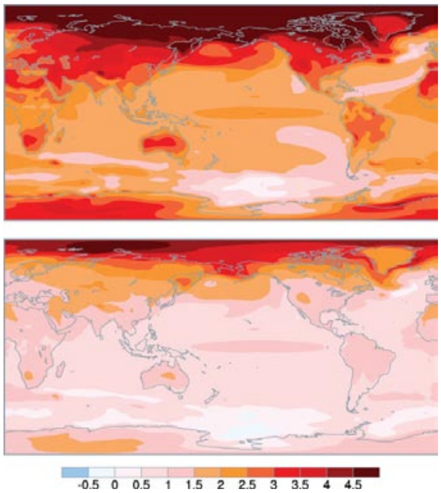
Tim Barnett and David Pierce of the Scripps Institution of Oceanography in San Diego, California, assessed the ability of the Colorado River to meet the demand from scheduled future water deliveries under different climate change scenarios. The authors found that under a conservative scenario of 10 per cent less runoff, expected water deliveries will fall short by 2040, and that with 20 per cent less runoff, water supplies will be inadequate to meet demand by 2025.

By mid-century, shortfalls are anticipated to exceed 1 billion cubic metres of water each year, equivalent to the water usage of 1.6 million households. Given the expected influx of 20–30 million people to the region by 2050, the authors conclude that drastic changes in water use will be necessary to prevent regular shortages.

Alicia Newton

MITIGATION

Cuts curb impacts



GRAPHIC COURTESY GEOPHYSICAL RESEARCH LETTERS, MODIFIED BY UCAR

Geophys. Res. Lett. **36,** L08703 (2009)

Some of the worst potential impacts of climate change — such as loss of Arctic sea ice and permafrost — could be minimized if greenhouse gas emissions were cut 70 per cent this century. Those are the reductions required to stabilize atmospheric concentrations of the gases at 450 parts per million (p.p.m.), above which there is a greater than 30-per-cent risk of dangerous climate change.

Warren Washington of the US National Center for Atmospheric Research in Boulder, Colorado, and colleagues used a suite of models to assess how the climate would respond to a business-as-usual emissions scenario, in which atmospheric concentrations reach 800 p.p.m. this century, and a mitigation scenario, in which greenhouse gases are stabilized at 450 p.p.m. Under the mitigation scenario, average surface temperatures would rise by only 0.6 °C — a quarter of that expected under business as usual. Moreover, Arctic warming would drop by 3 °C, potentially deadly heat waves would be 55 per cent less intense and at least eight centimetres of sea level rise could be averted.

The investigators note that such dramatic emissions cuts may not be politically or economically feasible but nevertheless urge policymakers to adopt targets and embrace green technology, conservation practices and carbon-sequestration programmes to avoid the most severe consequences of climate change.

Alicia Newton

The exit strategy

MYLES ALLEN[1,*], DAVID FRAME[1,2], KATJA FRIELER[3], WILLIAM HARE[3], CHRIS HUNTINGFORD[4], CHRIS JONES[5], RETO KNUTTI[6], JASON LOWE[7], MALTE MEINSHAUSEN[3], NICOLAI MEINSHAUSEN[8] & SARAH RAPER[9]

Emissions targets must be placed in the context of a cumulative carbon budget if we are to avoid dangerous climate change.

The build-up to the December 2009 Conference of the Parties to the Kyoto Protocol in Copenhagen has brought renewed impetus to calls for immediate action on climate change[1]. Many countries have agreed to aim to limit global warming to 2 °C above pre-industrial levels, with some calling for temperature targets as low as 1.5 °C (ref. 2). As past greenhouse gas emissions have already committed us to warming of around 1 °C, and given the inertia in both the climate system itself and in human systems such as energy, transport and food production, urgent action is clearly required if these targets are to be achieved. So far, so familiar: but this is where the agreement ends. Should we be aiming to stabilize atmospheric composition at (or at the equivalent of) CO_2 concentrations of 450 or 350 parts per million[2,3]? What should emission targets be for 2020 or 2050, and will they be low enough to avoid dangerous climate change? And why can't climate scientists just answer these simple questions?

Two companion papers[4,5] in this week's issue of *Nature*, addressing the question of what it will take to keep warming to 2 °C, present both a challenge and an opportunity for the climate-change mitigation debate. Both highlight the importance of the long view. Meinshausen *et al.*[4] argue that emission levels in 2050, or cumulative emissions to 2050, are robust indicators of the probability of temperatures exceeding 2 °C above pre-industrial values by 2100. Allen *et al.*[5] take an even longer view, exploring the impact of CO_2 emissions over the entire 'anthropocene'. They argue that keeping the most likely warming due to CO_2 alone to 2 °C will require us to limit cumulative CO_2 emissions over the period 1750–2500 to 1 trillion tonnes of carbon (1 Tt C; see Fig. 1). Warming due to other greenhouse gases[4] and uncertainty in the response[4,5] means that we may well have to accept an even lower limit to have any realistic chance of avoiding 2 °C of anthropogenic warming. So with more than 0.5 Tt C released already since pre-industrial times, it may well turn out that we can only afford to release less than the same again, possibly much less, with many times that amount in fossil-fuel reserves remaining underground[6].

Crucially, both studies argue that it is the accumulation over time of emissions of very-long-lived greenhouse gases like CO_2 that principally determines the maximum projected warming. In principle, emissions in any given decade matter only insofar as they contribute to the cumulative budget, although in practice, for most plausible emission scenarios, 2050 emissions are a strong indicator of the likely cumulative total[4]. These new results are not incompatible with current proposals for near-term emission targets: the small size of the cumulative emission budgets to 2050 reinforces the need for global CO_2 emissions to peak around or before 2020 so that emission pathways remain technologically and economically feasible[7].

The challenge these results present to the climate mitigation debate, however,

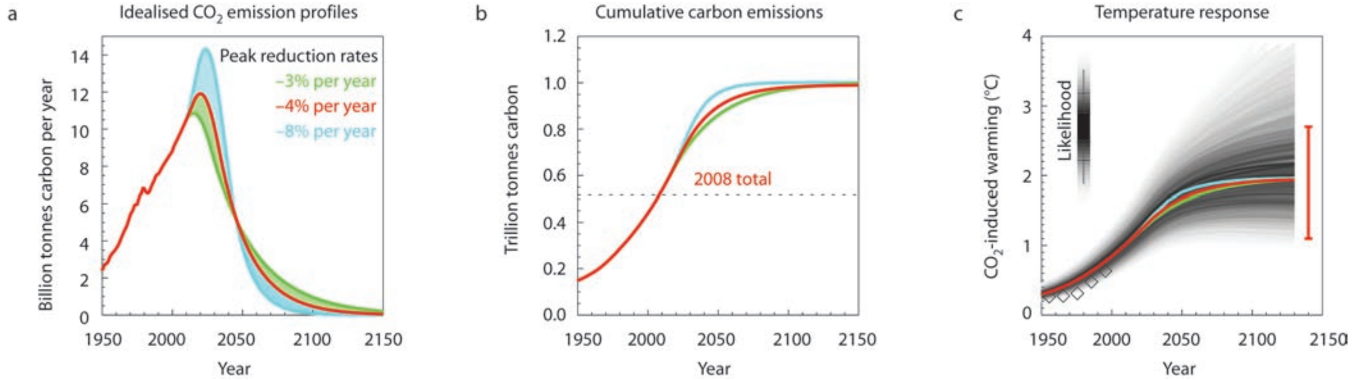


Figure 1 Idealized emissions. Shown are three idealized CO2 emission paths (**a**) each consistent with total cumulative emissions (**b**) of 1 trillion tonnes of carbon. Varying the timing of emissions alone has almost no impact on projected temperatures (**c**) relative to uncertainty in the climate system's response (grey shading[5] and red error bar[4,5]), provided the cumulative total is unaffected (the two blue shaded regions in a have the same area, as do the green); but the higher and later emissions peak, the faster they have to decline to stay within the same cumulative budget. Diamonds in **c** indicate observed temperatures relative to 1900–1920.

is that some might seize upon them as evidence that, if cumulative emissions are what really matters, then there is no point in worrying about emissions next year. But having taken 250 years to burn the first half-trillion tonnes of carbon, we look set, on current trends, to burn the next half trillion in less than 40. No one could credibly suggest that we should carry on with business as usual to the 2040s and then somehow suddenly stop using fossil fuels, switch to 100 per cent carbon capture or just shut down the world economy overnight. Conversely, others might argue that CO_2 emissions will always continue "because we have to eat and breathe", so if warming scales with cumulative emissions, temperatures are doomed to rise forever and we may as well give up. Against this, we would argue that a world in which emissions are 80–90 per cent lower than they are now would be so different from anything we can conceive today that it is absurd to rule out categorically the possibility of zero net emissions for any sector.

But this new evidence also presents an opportunity to clarify the terms of the debate. As the impact of cumulative CO_2 emissions can now be inferred primarily from quantities we can observe, it is very difficult to fudge the implications: the more CO_2 we dump into the atmosphere, the higher the committed warming. A single simple metric linking cumulative emissions to peak warming, or 'cumulative warming commitment'[5], reduces the many 'degrees of freedom' that policy-makers have to contend with. For example, Meinshausen *et al.*[4] argue that peaking global emissions before 2020, cutting them at least 50 per cent below 1990 levels by 2050 and continuing reductions thereafter gives us a reasonable chance of staying within a budget consistent with limiting warming to 2 °C, but securing agreement on this will undoubtedly be hard. This is where acknowledging the principle of a cumulative budget could be helpful: the higher emissions are allowed to be in 2020, the lower they will need to be in 2050 to stay within the same overall budget. From this perspective, the argument for early emission cuts becomes primarily an economic and technical one: late and rapid reductions are risky, expensive and disruptive, and hence potentially politically infeasible. And the sooner we start, the more flexibility we have to adjust policies as new scientific information becomes available. Cutting emissions later also raises the issue of inter-generational equity, as the costs of very steep emission reductions in the future (assuming these are feasible) could well exceed the economic benefits of postponing mitigation.

BRONSWERK / ISTOCKPHOTO.COM

Half a trillion tonnes of carbon have been released into the atmosphere in the past 250 years.

Should we prescribe an explicit cap on cumulative CO_2 emissions alongside shorter-term targets? This is a political question, not a scientific one: as scientists, we can only note that the close link between cumulative CO_2 emissions and peak warming means that the scientific logic of some kind of limit is inescapable. More research is undoubtedly required to support a specific target, which would need to be further refined as soon as we have some real data on the climate system's response to falling emissions. At present, we can simply note that a limit on cumulative CO_2 emissions will be needed in principle, whether it is achieved through an explicit cap or emerges from a succession of shorter-term targets. Current evidence suggests that this limit is unlikely to be higher than 1 Tt C if the goal of limiting global warming to 2 °C is to have much chance of being met, and that it may need to be substantially lower.

By placing short-term targets in the context of a cumulative budget, we reduce the risk of missed targets breeding defeatism.

Even without specifying a number, acknowledging the principle of a cumulative budget for very-long-lived greenhouse gases has practical implications. Emission rates, not cumulative totals, matter for shorter-lived climate-forcing agents such as methane or aerosols. This places a fundamental limit on how far it makes sense to 'bundle' the impacts of different human influences on climate. So in agreeing on targets, trading systems and so on, we have to bear in mind what they mean for total cumulative emissions of CO_2 (and, perhaps, other very-long-lived species like nitrous oxide). Short-term measures that reduce 2020 emissions of potent but short-lived gases but commit to greater emissions of CO_2 overall could actually be counterproductive.

Any discussion of limits on cumulative emissions must not distract attention from the need for shorter-term targets. If the world's politicians were to stand shoulder-to-shoulder in Copenhagen and declare "we will not release the trillionth tonne" it would be an inspiring moment, but it would not actually require anyone to do anything before the next election. But by placing short-term targets in the context of a cumulative budget, we reduce the risk of missed targets breeding defeatism. Instead of "we missed the target for 2020, so we may as well give up" (or worse, "now there's nothing for it but geo-engineering") we'll be saying "we missed the intermediate target, so now it's going to be even more expensive to meet our overall goal of avoiding dangerous climate change". None of these messages is comforting, but at least the last one is accurate.

Given the scientific logic of a cumulative budget, it is also hard to avoid the conclusion that negative CO_2 emissions may eventually need to be considered. First, these may be needed to offset emissions from sources that cannot be eliminated quickly enough, such as food production. Second, if total emissions are limited, and we are not sure exactly what the limit is (but the evidence suggests it may not be too far away), then there is a good chance we will find out too late that we have exceeded it[8]. Our descendants in the second half of this century, knowing much more about climate change and its impacts than we do, may decide that they need to intervene actively to reduce atmospheric CO_2 concentrations. To be credible, a cumulative cap perhaps ought to be accompanied by a commitment to develop the technologies to enable such intervention if necessary. The more we emit in the next couple of decades, the greater the risk that avoiding dangerous climate change might require negative net emissions at some point this century. Compared to the cost and risks of free-air capture, early emission reductions could rapidly start to look very attractive.

Over the coming years, many of us are likely to be asked to accept what we perceive as significant sacrifices to prevent dangerous climate change. In response, it is entirely reasonable to ask "what is the exit strategy?" How do specific short-term measures contribute to our long-term goal? The tight link between cumulative CO_2 emissions and peak warming helps cut through the tangle of different proposals. A tonne of carbon is a tonne of carbon, whether released today or in 50 years time. Emitting CO_2 more slowly buys time, perhaps vital time, but it will only achieve our ultimate goal in the context of a strategy for phasing out net CO_2 emissions altogether.

At some point in the past few years, without any fanfare, we burned the half-trillionth tonne. Somewhere out there, in a coal seam, hydrocarbon reservoir or some as-yet-undiscovered exotic form of fossil carbon, lies the trillionth tonne. Its fate, perhaps more than any other consequence of climate-change policy, is inextricably linked to the risk of dangerous climate change. Where will it be in the twenty-second century?

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A sensitive subject

Gauging how the planet will respond to rising emissions remains one of the biggest questions in climate science. **Mason Inman** looks at how close we are to answering it.

For decades, climatologists have been engaged in a quest for what some consider to be the field's holy grail: an accurate estimate of climate sensitivity. This number captures how temperature responds to greenhouse gases accumulating in the atmosphere — a vital quantity when emissions are increasing fast. If scientists could nail the number for sensitivity exactly, it would give a much clearer view of how global warming will change the face of our planet. It would also have big implications for policymakers, who want a concrete figure for how much CO_2 and other warming gases we can pump into the atmosphere while keeping the Earth's rising fever below dangerous levels.

"There is a true climate sensitivity," says Reto Knutti of the Swiss Federal Institute of Technology in Zurich. "We just don't know its true value." Our climate might be like a firm spring mattress, which only barely budges when you lay on it. Or it might be like memory foam, which you sink deep into. Or it's possible it could be very fragile: the legs might snap, collapsing the whole bed. We don't want to risk breaking the bed to find out whether we can sleep on it, so all we can do is poke and prod it with our fingers.

With only one planet Earth, scientists have had to estimate the sensitivity of our climate using a variety of such indirect methods, combining thought experiments with data from the past and model simulations of the future. This currently gives a best guess that temperatures would rise 3 °C if atmospheric concentrations of CO_2 doubled from pre-industrial levels, which many use as a rule of thumb for gauging the warming to come. But in the parlance of the Intergovernmental Panel on Climate Change (IPCC), the true value is 'likely' to be somewhere between 2 and 4.5 °C. This likely range, however, still leaves about a one-in-three chance that sensitivity is higher or lower — including the possibility that it could be 6 °C or more (Fig. 1). The fact that sensitivity estimates have a 'fat tail' — in other words, a fair chance of being much higher than the best guess — doesn't get enough attention, says climatologist Stephen Schneider of Stanford University in California.

> "There is a true climate sensitivity. We just don't know its true value."
> Reto Knutti

"We've been arguing about this for the last 40 years, and things are still not resolved," said Schneider at the Fall Meeting of the American Geophysical Union (AGU) in December, pointing out that there is still "a very large range of uncertainty that runs from 1.1 °C up to 'oh my god'". And while there might be consensus on the most likely value for sensitivity, Schneider says that it's more interesting to know what happens above and below that number. That's because the most severe climate impacts — such as droughts and floods, the collapse of ecosystems and the spread of disease — start to pile up as temperatures climb higher. "After all, we don't buy insurance for the median. We buy insurance for the one-per-cent outlier," says Schneider.

ALLOWANCE OVERSPEND

Since warming and many of its side effects will probably last for several hundred years or more — in human terms, forever — humanity has only one shot to tackle climate change. "We can't go for, say, one target for reducing emissions and hope that sensitivity is low, and if it turns out to be higher then just adjust and go for a much lower target," says Knutti. If we cross the line into dangerous warming — widely accepted to be 2 °C above pre-industrial temperatures or less — "there is essentially no way back for a long time", he says[1].

That's why agreeing on targets for greenhouse gas emissions — a key aim of the UN climate policy talks in Copenhagen this December — is thought to be so crucial. But because the system may respond more or less than expected to our emissions, we may need more than just targets to avoid overshooting the 2 °C limit, concludes a new study led by Myles Allen and David Frame of Oxford University, published in this week's *Nature*[2]. They say that to avoid dangerous warming from CO_2 alone, we'd need to limit all of humanity's emissions, stretching from the dawn of the industrial age to the distant future, to less than 1 trillion tonnes of carbon. So far, we've already burned through about half of that allowance.

However, some of the modelled climates they consider warmed a lot in response to CO_2, and some not so much, though all the simulations are thought to be fairly realistic. If the more sensitive models are correct, our overall allowance may be even smaller than

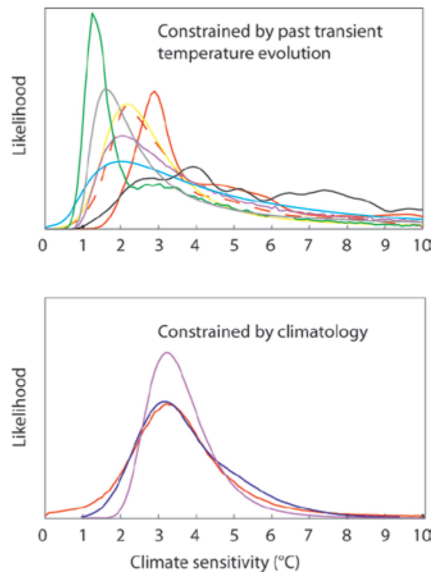

Figure 1 Range of responses. Studies estimating the climate's sensitivity give a large range of possibilities, but they agree that the most likely value is 3 °C. Some scientists worry, however, about the 'fat tail', showing a small but real possibility that the sensitivity could be high — 6 °C or even more. Graph adapted from the IPCC's Fourth Assessment Report[9].

DAGELDOG / ISTOCKPHOTO.COM

Underestimating climate sensitivity could mean a pile-up of severe impacts, such as floods, as temperatures climb higher than expected.

1 trillion tonnes of carbon. Then we'd be much closer to hitting the wall, the time when global greenhouse emissions have to be reduced to nearly nothing to keep below 2 °C. If warming climbs above this threshold — which many scientists fear it will[3] — the possibility of high climate sensitivity becomes especially worrying.

Yet despite using every trick in the book to try to gauge the risk of that happening, many climate scientists feel that recent decades of research have seen little progress on the issue. "It's quite sobering to look back and ask how far we've come," says Björn Stevens of the Max Planck Institute for Meteorology in Hamburg, Germany. "On sensitivity, there's not been much progress." Schneider agrees. "We still have this uncomfortable problem of the fat tail that we have to worry about," he says. "I don't think we're going to have that one knocked anytime soon — not in the next few decades."

Though sensitivity isn't the only source of uncertainty about how climate change will affect the Earth, "it's the uncertainty in sensitivity that dominates long-term projections", Knutti says. There's also uncertainty in how the carbon cycle will respond to change, which will determine how much of the emitted greenhouse gases are absorbed by the land, oceans and organisms. Even more complex is the uncertainty about how climate change will affect ecosystems or economies. But "as far as climate sensitivity is concerned, the uncertainty is at least a factor of three", Schneider says. This essentially is the difference between relatively mild and extreme warming, making it a key unknown for scientists working on the climate system.

PERSISTENT PROBLEM

Academics have been trying to estimate this number from the dawn of climate science more than a century ago. Since then, researchers wanting to know how greenhouse gases would affect the planet have used a simple thought experiment: double the amount of CO_2 in the air, and then hold that level steady for a hundred years or more, until the planet's temperature stops rising and it settles into a new, hotter state. The somewhat artificial but handy method was devised by Nobel Prize-winning chemist Svante Arrhenius, who first estimated sensitivity.

As far back as the 1890s, Arrhenius realized that there are crucial responses, known as feedbacks, in the climate system that make it difficult to calculate how sensitive it is to changes in atmospheric carbon dioxide. He factored in only one of these, albeit the biggest one: the heating caused by evaporation. Rising greenhouse gases trap heat, causing increased evaporation, and because water vapour is itself a powerful greenhouse gas, it amplifies the heating. After two years of gruelling calculations by hand, Arrhenius estimated that doubling CO_2 would warm the planet by 5.5 °C.

Since then, simulations of the climate have gotten far more complex and are more reliable, drawing on sophisticated computer models, temperature data from the past century and knowledge of ancient climate over tens of thousands of years. Some argue that in fact we now know the climate sensitivity quite well. Speaking at the AGU Fall Meeting, climate scientist James Hansen, director of NASA's Goddard Institute for Space Studies in New York, said, "The climate sensitivity is really nailed. It is three degrees for doubled CO_2, plus or minus half a degree." The method Hansen draws on — looking at the state of the planet during the last ice age, 20 thousand years ago — does have advantages. "The physics is exact. It is not modelled," Hansen argues. "All of the feedbacks operate correctly."

But others remain unconvinced. The planet was a much different place many thousands of years ago, with thick ice sheets covering much of North America and western Europe, and we can't just assume that the sensitivity now is the same as it was then, says Knutti. "The further back you go, the more critical this assumption gets," he says. "Personally, I don't trust the estimates from paleoclimate so much."

Besides Hansen's favoured method, all other methods of estimating the sensitivity give much fuzzier answers. Studies of the past century's temperatures, for example, suggest that sensitivity is probably between 1.5 °C and 6 °C. The longer record from the past millennium gives an even wider range, because the underlying measurements — from tree rings, sediment cores and other sources — are less certain than modern thermometer readings. Eruptions of large volcanoes serve as natural climate-cooling experiments that researchers can use to hone their estimates of sensitivity. But this method also gives a range of possible sensitivities that leaves open a fair chance that the true value is very high — as much as 6 °C or more.

The IPCC used expert judgment to select from these varied estimates and determine a narrower 'likely' range of 2–4.5 °C. Some have argued for a more rigorous approach to combining data sets, such as is possible with Bayesian statistics. This technique provides a way to take one set of information and update it as new data come in, giving a more comprehensive picture than can be achieved with any single method. Using this approach to combine modern-day sensitivity estimates with four other kinds of proxy measurements stretching back 700 years, Gabriele Hegerl at the University of Edinburgh, UK, and colleagues narrowed the possibility that sensitivity is above 4.5 °C to just

15 per cent. Also using the Bayesian method, but with temperature records taken after volcanic eruptions and from the last ice age, James Annan and Julia Hargreaves at the Japan Agency for Marine–Earth Science and Technology in Yokohama cut this probability back further to just five per cent[4].

This approach hasn't yet caught fire in the climate science community, however. "Nobody has presented any clear case that our arguments are wrong, but nobody has come out and endorsed it either," Annan says. "I don't really think there is any magic bullet that is going to greatly improve estimates," he adds. "But I think the most promising approach is do the sort of thing we've been doing, trying to combine the evidence that we already have." One worry is that the various estimates used in such analyses might not be truly independent. Unless possible overlaps are meticulously accounted for, then results can get factored in more than once, which could create a false sense of certainty — one climate scientists are keen to avoid[5].

BIG PICTURE

An alternative approach to understanding sensitivity has involved getting a better handle on how complex processes — such as cloud formation — are approximated in climate models. Just as an impressionist painting can capture a scene despite using broad strokes, model approximations aim to capture the overall effect of how such processes work in reality. By adjusting their inner workings, called parameters, and running the models many times over with various combinations of these fine-tunings, scientists have been able to get a sense of the range of possibilities for sensitivity as well as the reasons for possible outliers.

The answers from some such studies have been less than reassuring. An effort to produce climate predictions up until 2080 using time on volunteers' computers, Climateprediction.net has run climate simulations thousands of times and found that slightly tweaking parameters generates simulations that show climate sensitivities below 2 °C or above 11 °C — a huge range[6]. This has spurred much debate over whether the range reflects an actual set of possibilities in the real world or whether it simply reveals how climate models work.

Also up for debate is whether improving the models' approximations of complex processes — such as the degree to which clouds are likely to counteract warming — will narrow sensitivity. While research underway to improve the parameterizations for clouds will probably be included in several global climate models that will shape the IPCC's Fifth Assessment Report, such efforts may be in vain, at least when it comes to estimating sensitivity. It has long been known that uncertainties in the parameters for some model components, such as clouds or ocean currents, generate estimates at the high end of the spectrum. Gerard Roe and Marcia Baker at the University of Washington in Seattle say that this is inevitable and limits how well scientists can estimate the sensitivity[7]. "That shape is immutable, no matter what improvement you make in the parameters," Baker says. "You don't need a fancy explanation."

> "I don't think we're going to reduce the uncertainty anytime soon. I've moved on to say we just have to cope with it."
> David Stainforth

But some think there may still be a way around this apparent limit. Nathan Urban and Klaus Keller at the Pennsylvania State University in University Park recently looked at two parameters crucial for sensitivity: the uptake of heat by the ocean surface and the rate at which heat is mixed through the oceans. These two components have opposite effects on climate sensitivity, so for the sensitivity to be high the ocean must be taking up a lot of heat but not distributing it well into deeper waters. Combining measurements could help rule out the chance of such components lining up to produce the highest possible sensitivity, Urban and Keller argue. It's like playing twenty questions. You start with only a vague idea of what you're trying to guess — say, it's some kind of animal. But as you narrow down the possibilities — it's dark in colour, and about the size of a shoe box — then you can make a good guess: it's a black cat. Similarly, Urban and Keller argue, by collecting better data on complementary aspects of the climate and balancing them against each other, it might be possible to pin down the climate sensitivity[8].

CALL OFF THE QUEST?

But Roe and Baker's argument has some convinced that it's time to give up on trying to narrow the range of possibilities. "An upper bound on the climate sensitivity has become the holy grail of climate research," wrote Allen and Frame in *Science* in 2007. "As Roe and Baker point out, it is inherently hard to find. It promises lasting fame and happiness to the finder, but it may not exist. Time to call off the quest," they concluded. David Stainforth of the London School of Economics, leader of the Climateprediction.net project, agrees. "I don't think we're going to reduce the uncertainty anytime soon," he says. "I've moved on to say we just have to cope with it."

Even if there's no inherent limitation on scientists' ability to figure out the climate's sensitivity, since it's proven so hard to home in on, learning to live with the uncertainty might be the safest bet. But it's not a reason for inaction, Schneider stresses. "Policy depends upon a generational transformation of basic energy production systems," he says. "You can't wait until you know. By that time it's way too late to do anything about it. That's not how anybody treats cancer, that's not how anybody makes investments, that's not how the military operates. And we are not entitled to this luxury."

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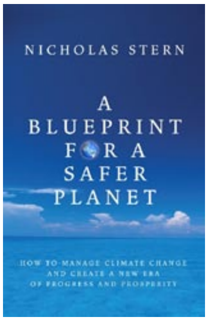
Stern advice for Copenhagen



BLUEPRINT FOR A SAFER PLANET

by Nicholas Stern

The Bodley Head: 2009. 256pp. £16.99

In this new book, economist Nicholas Stern makes a sweeping proposal for a global climate deal.

"The claim 'We cannot afford it' is not very different from 'we are not sufficiently bothered to deal seriously with climate change'" — except that the latter view would clearly be reckless, says Nicholas Stern in his new book. Filled with the urgency of immediate action on climate change, *Blueprint for a Safer Planet* offers the exciting possibility of an affordable, effective global deal that could be adopted at the UN negotiations in Copenhagen in December.

A former chief economist at the World Bank, Stern has played a central role in climate policy debates since his 2006 review on the economics of climate change. Commissioned by the British government, the Stern Review argued that the risks of climate change under 'business as usual' emissions scenarios were intolerably large. Moreover, most of the threatened damage could be avoided through expenditures of roughly one per cent of the world's economic output for several decades. Stern contended that a global agreement perceived as equitable by all was both possible and necessary to avoid such risks.

Stern's latest offering updates his arguments from 2006. For a start, the science has grown even more ominous, prompting him to revise his recommendation for the upper limit at which we should aim to stabilize greenhouse gas concentrations. Now he says they should be held below 500 parts per million (p.p.m.) of CO_2-equivalent (roughly 450 p.p.m. of CO_2 alone) — compared to 550 p.p.m. CO_2-equivalent in the Stern Review — and then reduced further over time if necessary. Meanwhile, there is growing evidence that numerous technologies and options are available for emission reduction. Adaptation can help, but it is not, alone, a viable alternative to reducing emissions.

One of the high points of the new book is Stern's response to some of his fiercest critics — economists who favour going slow on efforts to mitigate climate change. In non-technical language — using not a single graph, equation or acronym — Stern explains that the argument for acting later, rather than now, is based on two mistaken premises. It uses implausibly low assumptions about expected climate damages, together with a high 'discount rate', which in economic terms means that benefits in the far future are not important today. If near-term risks are small and the far future doesn't matter, then the 'justification' for inaction follows directly. But as Stern points out, the choice of discount rates — and how much to value the future — is an ethical decision, not a technical one.

This book, however, is not fundamentally aimed at advancing knowledge of either science or economics. Rather, it uses what we know about those fields as the basis for a sweeping policy proposal. With the Copenhagen conference fast approaching, the book outlines a vision for a global deal that could be acceptable to all major parties to the negotiations.

Stern proposes six essential elements that are jointly required for adoption of a global agreement. On the issue of goals, he says that developed countries must immediately adopt binding targets to reduce greenhouse gases to at least 80 per cent below 1990 levels by 2050. Developing nations must take on binding targets no later than 2020 requiring that their emissions reach a peak and start to decline before 2030 — and sooner for the fastest-growing economies. In Stern's proposal, national or regional carbon trading schemes would be integrated into a global system. International funding would be provided on two fronts, firstly to allow developing nations to adapt to the early stages of climate damages and secondly to halt deforestation, one of the cheapest opportunities to reduce carbon emissions. Stern also calls for demonstration, sharing and further development of clean energy technologies.

The costs of all of this are perhaps one to two per cent of world output for some years to come. International funding required from rich countries might be around 0.3 per cent of gross domestic product — roughly ten per cent of current military spending, or one per cent of total government spending. There is no way to argue that this is unaffordable. Since the threat is real and devastating, protection at that price is a bargain.

The book has its ups and downs, and was produced on a tight schedule; some passages comment on the November 2008 election of Barack Obama, while others refer in the present tense to the high oil prices and weak US dollar of early 2008. The apparently obligatory chapter on local, private-sector and non-profit initiatives offers a bewildering collage of isolated activities with little sense of their relative importance. The United States has just completed an eight-year experiment studying whether local, private and non-profit initiatives can achieve significant emission reductions in the absence of national leadership; the answer turns out to be 'no'.

Stern is unfailingly diplomatic, frequently referring by name to those he agrees with but almost never to those he disagrees with. One prominent American economist has mocked Stern's "lofty" sentiments and intemperately attacked him for foisting the views of the "British Empire" on the world. Stern replies that "this statement was surprising as he is a scholar and a gentleman. He is simply misguided and misleading on the key economic issues discussed in this chapter, as we shall show."

My biggest question about Stern's analysis is whether it understates the severity of the problem and the extent of the action required. Climatologist James Hansen, among others, has argued that stabilizing atmospheric carbon dioxide concentrations at 450 p.p.m. would leave them at a dangerously high level and has called for a safer limit of 350 p.p.m. Stern responds that his global deal, putting us on track to 450 p.p.m., is at the outer limits of what is politically feasible in the near term; achieving Stern's goals for 2050 would position us to revise global targets downward in the future, if needed.

Finally, there is a striking congruence between parts of the Stern proposals and parts of UK climate policy, although it is not clear which came first: earlier government policies may have shaped Stern's sense of what is possible; conversely, the Stern Review has served as a basis for revisions of some government positions. Coming from a country that has done less on the issue than Britain to date, I don't view this as a mark against either Stern or his government. The British Empire was rarely so skilfully and persuasively served by its citizens and scholars.

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Crunch time for the Clean Development Mechanism?

Anna Barnett reports on the recent dip in projects entering the UN emissions offsetting programme.

A UN programme supporting clean technology projects in the developing world is beginning to shrink as global economic woes and political uncertainty take their toll, say researchers. Set up as part of the Kyoto Protocol, the Clean Development Mechanism (CDM) lets developed countries buy credits assigned to emissions-reducing efforts in poorer nations in lieu of cutting greenhouse gases at home. The number of projects entering the CDM's approval process has recently started to slide. On average, 112 projects per month were submitted from November 2008 to January 2009, below the 2008 monthly average of 130. Slumps this size have occurred before, but February had only 75 new projects submitted, a low not seen since 2006, when CDM activity was just starting to pick up (Fig. 1). And because projects often go through a lengthy period of development before seeking approval, "we may well see a further drop in the data in the next months" in response to the financial crisis, says Glenn Hodes, a senior economist with the UN Environment Programme Risoe Centre at the Technical University of Denmark in Roskilde.

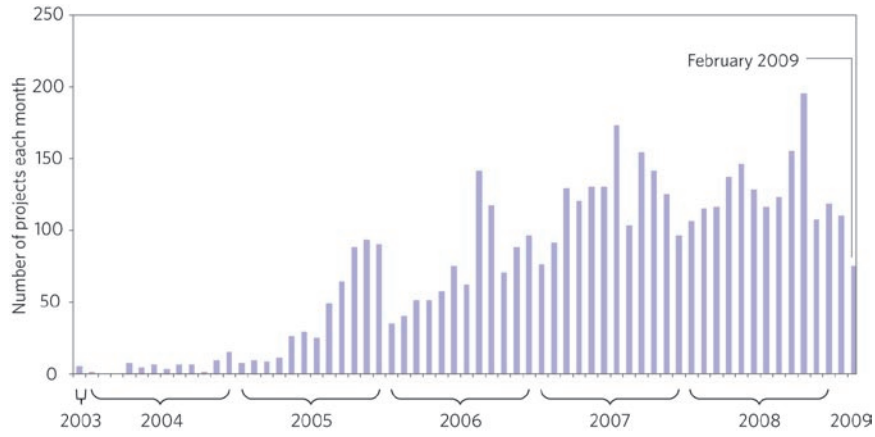

Figure 1 Number of CDM projects starting the evaluation process each month. Adapted from UNEP Risoe CDM/JI Pipeline Analysis and Database, March 1st 2009 (ref. 1).

Fewer projects mean less CDM-driven emissions cuts. In March analysts at the Risoe Centre lowered their estimate of total greenhouse gas emissions likely to be offset by the CDM during the period 2008–2012. In response to the dip in projects entering the scheme, they shaved 2 per cent, or 33 million Certified Emissions Reduction credits (CERs) — each representing greenhouse gas emissions equivalent to one tonne of CO_2 — off their previous month's estimate[1]. Similarly, at the market research firm Point Carbon, the estimated pool of CERs for 2008–2012 has shrunk by 6 per cent, or 110 million tonnes of CO_2, since January.

In a 2009 poll of carbon market investors by Point Carbon, 60 per cent said they had scaled down, delayed or cancelled investments in carbon credit projects because of the economic downturn. This includes projects undertaken in developed countries, under a Kyoto mechanism known as Joint Implementation, as well as CDM ventures. In addition to difficulty obtaining loans in the current economy, CDM project backers have suffered a steep decline in the value of credits. At their nadir in mid-February, benchmark CERs traded at a quarter of their early-September price. Analysts say demand has dropped because the recession is hitting industry, damping down European emissions — and some cash-strapped companies are selling off their EU allowances, the credits they hold as part of the European carbon-trading scheme.

But the fall-off in new CDM projects would have happened without the financial crisis, says Arne Eik, an analyst at Point Carbon. "We're getting closer and closer to 2012," he says, referring to the date when a new global climate treaty, being negotiated in Copenhagen this December, will take effect. The deal is intended to replace the Kyoto Protocol, but until it's struck, the future role of the CDM — and revenues from its projects — can't be guaranteed. "If we get some good signals for the CDM in Copenhagen, I would expect it to increase again in spite of the difficult economic times," says Eik.

Others also expect the trend will soon turn around. Many of the companies most active in the CDM market anticipate an infusion of funds before the end of the year, according to the Point Carbon poll. Of those sampled, 46 per cent of CDM investors predicted they would increase their project investments in 2009, compared with 23 per cent who said investments would decrease or cease. A shift in US politics may be behind the optimism, says Eik, with President Obama pushing a national emissions cap and aiming for agreement in Copenhagen. These are good omens for carbon-cutting projects, he adds, even if those projects end up being part of a whole new framework. "It's not necessarily going to be the CDM as we know it," he says.

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