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.

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"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

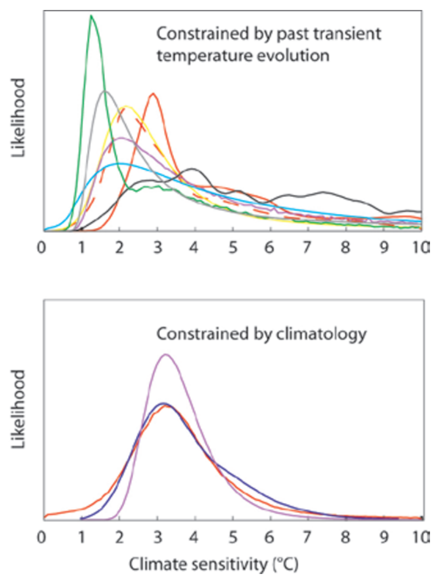

Figure 1 Range of responses. Studies estimating the climate's sensitivity give a large range of possibilities, but they agree that the most likely value is 3 °C. Some scientists worry, however, about the 'fat tail', showing a small but real possibility that the sensitivity could be high — 6 °C or even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

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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."

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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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