confirm that, together, the man-made factors cause substantial drying in the Sahel.

The team also found that the amount of drying depends on the strength of the inter-hemispheric sea surface temperature gradient. This gradient is enhanced by Northern Hemisphere aerosol emissions but, in their model, it is suppressed by rising greenhouse-gas concentrations, so the drying effect on the Sahel is strongest when the sulphate aerosols act in isolation.

The study moves beyond previous work on the causes of drought in the Sahel by testing the sensitivity of these findings to the formulation of the model used to generate them. The researchers do this by exploiting a remarkable set of simulations of the way in which the climate system responds to changes in greenhouse-gas concentrations and aerosol emissions over time. Drawing on the computer power of volunteers from around the world, the Climateprediction.net initiative has run thousands of climate model simulations, each of which represents aspects of the climate system — from the chemistry of the atmosphere to cloud microphysics — in a slightly different way. Together, these simulations are known as a 'perturbed-physics ensemble' and can be used to explore whether climate trends simulated by a 'parent' model are robust to small changes in the way climate processes are represented.

As part of this initiative, over 1,500 model runs were forced by historic emissions of greenhouse gases and sulphate aerosols. The vast majority of these simulations produced drought in the Sahel, with the magnitude of the drying matching the trend observed between 1940 and 1980 quite well. Another set of more than 500 simulations was forced by the same rise in greenhouse-gas concentrations, but a weaker forcing by Northern Hemisphere aerosols. These simulations showed no drying trend in the Sahel, confirming that the main cause of the drought was aerosol emissions from industrialized countries. They also showed that this result is robust to small changes in the way in which climate processes are represented in the 'parent' model.

The team's results provide convincing evidence that sulphate aerosol emissions contributed to the decline in rainfall in the Sahel between 1940 and 1980. This is not the end of the story, however. For one thing, the ensembles appear to underestimate the natural variability in Sahel rainfall, reducing confidence in the team's estimate of the relative roles of anthropogenic forcing and natural variability in determining rainfall anomalies. Also, the 'parent' version of the model that the team uses (and possibly the perturbed-physics ensemble too) simulates a wetter Sahel in response to rising greenhouse-gas concentrations, when other coupled models do the opposite and accordingly attribute the twentieth-century drought to emissions of both aerosols and greenhouse gases[9]. Furthermore, the simulations do not include feedbacks involving changes in vegetation and dust, which are likely to be important[10,11].

It might be possible to distinguish the responses of rainfall in the Sahel to greenhouse gases and to aerosols by analysing their seasonal signatures: models indicate that the effect of aerosols is strongest in summer, whereas greenhouse gases influence the timing of the rains[12], decreasing precipitation during spring and increasing it during autumn. But this analysis, along with a more realistic representation of natural variability, vegetation dynamics and dust processes must wait for future generations of climate models.

Despite its limitations, the work of Ackerley and colleagues[5] provides the firmest evidence yet that sulphate aerosol emissions from Europe and North America contributed to the devastating droughts of the 1970s and 1980s. As sulphate aerosol burdens grow in Asia, South America and other emerging economies, we can expect that regional rainfall patterns will be modified in ways that could either exacerbate or mitigate the effects of global warming. As the Sahel drought teaches us, preparing for climate change requires that we understand the interplay of global and regional anthropogenic forcings. ❐

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ECONOMICS

# Opportunities from uncertainties

The inability to verify nations' reported progress towards emission-reduction commitments is a stumbling block in climate change negotiations. Narrowing uncertainties in the global carbon cycle could help overcome this obstacle.

Gary W. Yohe

Climate change negotiations collapsed in Copenhagen 18 months ago in part because countries that might have signed up to a global agreement worried that others would be able to exaggerate their progress in reducing emissions (Fig. 1). In essence, it would be possible to cheat against negotiated commitments without the threat of detection. Implementing the infrastructure needed to monitor and verify emissions at the national level does not offer a practical solution to this sticking point, because it would be both difficult and expensive[1,2]. Writing in *Philosophical Transactions of the Royal Society A*, Adam Durant and colleagues[3] argue that reducing uncertainties in the global carbon balance would be a relatively cheap and easy way of checking reported emissions, potentially saving billions of dollars in climate-related damages by encouraging countries to comply with their emission-reduction targets.

It is well known that the ability to verify reported emissions is essential for bringing nations on board for a legally


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**Figure 1 |** Negotiators at the United Nations climate change conference in Copenhagen in 2009. A key sticking point in these 'crunch' negotiations was the need for emission reductions to be measurable, reportable and verifiable. Durant and colleagues[3] show that relatively inexpensive measures to reduce uncertainties in the global carbon cycle would allow reported carbon dioxide emissions to be cross-checked against atmospheric carbon dioxide concentrations at the global scale, which might provide an incentive for countries to report their emissions more accurately.

binding climate agreement[4]. Negotiators have, however, also come to realize that countries are not fond of the idea of an international body such as the United Nations looking over their shoulder to see whether they are 'free-riding' on the efforts of others. This is one reason why many nations, including China, have heretofore refused to join a legally binding agreement, despite having begun their own domestically monitored policies to cut emissions at home.

Estimates of global anthropogenic carbon dioxide emissions can, in theory, be verified by cross-checking them against changes in the atmospheric concentration of carbon dioxide. However, human activities are not the only processes that determine the amount of carbon dioxide in the atmosphere. The terrestrial biosphere and the oceans also play a central role, taking up more than half the carbon dioxide emitted by human activities each year. Taken together, the uncertainties associated with these natural sinks can obscure the link between anthropogenic emissions and atmospheric concentrations of carbon dioxide, making it impossible to confirm reported emissions by monitoring the latter. This ambiguity gives individual countries 'cover' against detection should they choose to exaggerate the extent of their emission reductions.

Durant and colleagues[3] estimate the potential for reducing the uncertainty associated with each component of the global carbon cycle, as well as the economic cost of doing so. They conclude that the uncertainties associated with the land and ocean carbon sinks could be reduced to the level associated with man-made emissions at relatively low cost. The reduction could be achieved by measures such as improving monitoring infrastructure — for example, the network of ships that measure carbon dioxide in the upper ocean — and improving models of carbon fluxes. This narrowing of uncertainties in natural sinks would reduce non-compliant countries' protection against being detected. However, Durant *et al.* take this a step further, proposing that the diminished protection against detection might give nations an incentive to report their emissions accurately and thereby improve compliance with emission-reduction targets.

Assuming this is the case, the team calculated the economic gains that improved compliance would bring. They did so by analysing four scenarios in which developed countries commit to reducing their emissions by 30% relative to 2008 levels, and developing countries commit to capping their emissions at 130% of 2008 levels, from the present day until 2100. In the baseline scenario, all countries comply with their targets immediately. In a variant on this case designed to simulate a situation in which countries can cheat in their reporting, all countries' emissions remain 5% above their announced commitments throughout the simulation period. The 'excess' emissions relative to the baseline case in this scenario cause the mean net present value of climate damages to increase by about $10 trillion over the simulation period. In two other scenarios, countries comply with their commitments only after 2020 and 2030, at which time the monitoring infrastructure is assumed to have improved to the extent that counties no longer feel comfortable cheating. In these scenarios, the mean net present value of extra damages falls by 85% and 75%, respectively.

To Durant and colleagues, the main contribution of their work is the finding that the economic value of avoiding the harm caused by 'excess' emissions far outweighs the cost of reducing uncertainty in the carbon balance, at least at the global scale. To this reader, however, they sell themselves short by ignoring the wider context of their work. It is well understood that limited participation undermines any international policy regime, and it also makes sense that all nations that choose to participate in such a regime need to comply with it to ensure success. The real story here is that Durant *et al.* have highlighted a way of influencing countries' motivations to sign up to an international agreement, as well as their motivation to 'play by the rules' once they do so.

Nations will be less tempted to knowingly under-report their emissions if the likelihood of detection is larger, but only if they recognize that there are significant consequences to their being caught. If we were considering national policy imposed from above, standard economics would suggest setting fines equal to the marginal social damage of their actions divided by the likelihood of paying that fine[5]. Of course, threatening such a fine in an international context would only discourage nations from signing up to commitments. So, how do we inspire compliance without discouraging participation?

This is a question that must be answered in the context of the outline for long-term policy design summarized in the synthesis report of the IPCC's fourth assessment report; a document that was accepted unanimously by the same nations who participated in the United Nations climate negotiations. Recognizing that it is impossible to set policy for an entire century and beyond, these countries agreed that "responding to climate change involves an iterative risk-management process that includes both adaptation and mitigation"[6]. The operative word here is 'iterative'. It implies that climate policies will be adjusted from time to time on the basis of not only new advances in scientific understanding of how the climate system works, but also advances in political–economic understanding of how climate policies work.

Although detecting individual nations' non-compliance might be difficult, Durant and colleagues[3] have shown that detecting collective non-compliance against global targets is possible. Iterative adjustments to these targets will be required if a designated global indicator of policy success, such as global temperature, happens to track above (or below) required trajectories, for whatever reason. This will be a fact of life that nations will come to accept. However, nations will be more inclined to participate in flexible international agreements if they are more confident that they will not be punished unfairly in the adjustment process because others are behaving irresponsibly. The verification process described by Durant *et al.* would help build this confidence by making it more difficult for nations to blame 'excess' emissions from their non-compliance on uncertain natural causes.

Implementing a more transparent verification process of the sort that Durant and colleagues[3] envisage to support an iterative mitigation strategy would thus make the target adjustment process less arbitrary, by revealing the underlying causes of changes in atmospheric carbon dioxide concentrations more accurately. It would also make it potentially less punitive, by reducing the protection from detection that uncertainty about natural sources and sinks gives participating but non-compliant countries. Both of these factors should encourage responsible nations to participate in a global deal. If their proposals are correct, Durant and colleagues[3] have thus identified an economically justifiable investment that could help overcome one of the most important stumbling blocks in the negotiations. ❐

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