

Observational constraints on future climate: distinguishing robust from model-dependent statements of uncertainty in climate forecasting

Contribution to the IPCC Workshop on Communicating Uncertainty and Risk, May, 2004

M. R. Allen¹, B. B. Booth^{1,3}, D. J. Frame¹, J. M. Gregory^{2,3}, J. A. Kettleborough⁴, L. A. Smith⁵, D. A. Stainforth¹ & P. A. Stott³

1. Department of Physics, University of Oxford, UK (Clarendon Laboratory, OX1 3PU, UK & myles.allen@physics.ox.ac.uk)

2. Department of Meteorology, University of Reading, UK

3. Hadley Centre for Climate Prediction and Research, The Met Office (Reading Unit), Reading, UK

4. Space Science and Technology Department, Rutherford Appleton Laboratory, UK

5. Department of Statistics, London School of Economics, UK

Background: The IPCC Third Assessment Report (TAR) was strongly criticised for failing to present its headline projections of 21st century climate change in quantitative probabilistic terms¹. Although it was argued² that this accurately represented the literature at the time, quoting ranges of uncertainty with no indication of the likelihood of the actual climate straying outside these ranges will not be acceptable in the Fourth Assessment Report (AR4). Quantitative probabilistic climate forecasting raises fundamental challenges, in particular regarding the treatment of system response uncertainty or model error^{3,4}.

Sources of uncertainty in climate forecasting: AR4 will need to distinguish clearly between

1. Uncertainty in anthropogenic forcing due to different emission paths (“scenario uncertainty”)
2. Uncertainty due to natural variability, encompassing internal chaotic climate variability and externally driven (e.g. solar, volcanic) natural climate change (“natural variability”)
3. Uncertainty in the climate system’s response to external forcing due to incomplete knowledge of feedbacks and timescales in the system (“response uncertainty”)

These different sources of uncertainty need to be distinguished because they have very different policy implications. Scenario uncertainty is a special case because it is, to some degree, under policy control. Some uncertainties due to natural variability may be reduced by detailed observations of the current trajectory of the climate system, but typically on timescales of a few years, thereafter representing an irreducible lower bound on forecast skill even given complete knowledge of climate system behaviour. All aspects of response uncertainty are reducible in principle by the acquisition of new information, but it helps to distinguish between

- 3a Robust aspects (timescales, forecast variables) of response uncertainty that are unlikely to be revised substantially except on the timescale of climate change itself
- 3b Subjective aspects of response uncertainty that could be revised substantially with a change in expert opinion, the acquisition of new data or implementation of new models.

We will argue that the system may be sufficiently linear on anthropogenic climate change timescales for a useful distinction to be made, at least in principle, between these sources of uncertainty even though there are obvious interactions. For example, more sensitive climates will typically display higher levels of natural variability, and estimates of response uncertainty will typically depend on the scenario considered, particularly if constrained by past observations^{5,6}.

Relative importance of sources of uncertainty and implications for presentation: Studies undertaken since the TAR⁶ have demonstrated that response uncertainty dominates global temperature predictions over the first few decades of the 21st-century, while contributing about half the overall uncertainty in temperature projections to 2100, the remainder due primarily to scenario uncertainty. Natural variability is primarily important on decadal and sub-decadal timescales at the global mean level, but significantly more important at longer timescales on smaller spatial scales. The headline temperature projection figure (5d) in the TAR-SPM⁷ showed an inner “plume” representing scenario uncertainty alone (a single model forced with the range of SRES scenarios) and an outer “plume” showing combined scenario and response uncertainty (several models forced with the range of SRES scenarios). Even with such small samples,

uncertainties sum approximately in quadrature, so this presentation tends to exaggerate the role of scenario versus response uncertainty. The converse presentation showing response uncertainty as the inner plume (a single scenario forcing a range of models) suggests an almost negligible role for scenario uncertainty until the mid-21st-century, which is also potentially misleading. The use of an energy balance model suppresses the contribution of natural variability altogether. A more balanced presentation would be to show forecast plumes combining response uncertainty and natural variability for a (necessarily small) range of representative emissions scenarios, allowing the reader to visualise the impact of adopting different scenarios in the context of other sources of uncertainty in the forecast⁶.

Confidence versus likelihood in the presentation of uncertainty: No consistent distinction was made in the TAR between statements of *confidence*, reflecting the degree of consensus across experts or modelling groups regarding the truth of a particular statement, and statements of *likelihood*, reflecting the assessed probability of a particular outcome or that a statement is true. This needs to be resolved in AR4, because we need to communicate the fact that we may have very different levels of confidence in various probabilistic statements. For example, we might wish to argue we have a much higher level of *confidence* in the statement

A: “anthropogenic warming is likely to lie in the range 0.1-0.2°C per decade over the next few decades under the IS92a scenario” (TAR SPM)

than in the statement

B: “it is likely that warming associated with increasing greenhouse gas concentrations will cause an increase in Asian summer monsoon precipitation variability” (ibid.)

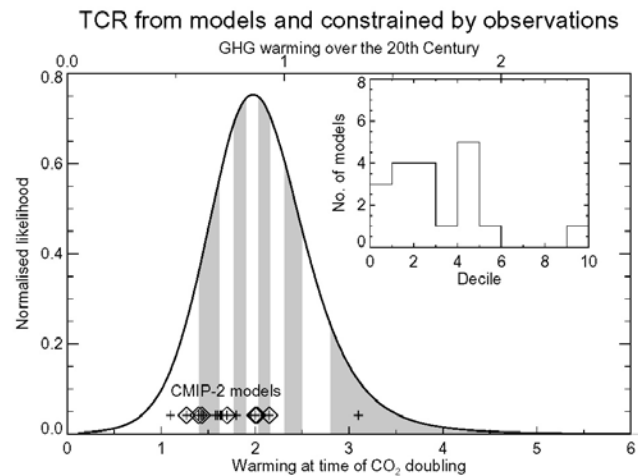
even though both can only be qualified by the same “better than two in three chance” *likelihood*. The first statement is based on the analysis of observed anthropogenic warming, the constraint of energy conservation and the assertion that no strongly non-linear global climate changes are anticipated in the coming decades. It is unlikely to change through the introduction of higher-resolution models, additional physical processes or changes in expert opinion. Although relatively weak in itself (“likely”), this statement of odds is reliable in the sense that the level of uncertainty is unlikely to be revised other than downwards as more data are acquired. In contrast, the second statement represents the current consensus across climate models, and the uncertainty estimate could be revised either up or down as the next generation of models and additional physical processes are considered. Hence, although both statements refer to the same level of probability, they have very different policy implications: there is little point in postponing policy decisions in case the scientific community changes its mind on the first statement, because it is unlikely to do so, whereas new modelling results are much more likely to impact on the second.

Robust, observationally constrained, STAID probabilistic forecasts: Probabilistic statements that rely on constraints provided by observations, making use of climate models simply to identify robust relationships between observable and forecast quantities, have a very different status to statements based on model inter-comparison studies or surveys of expert opinion. Underlying statement A above, both basic theory and a range of results from climate models suggest near-linear relationships, or transfer functions⁵, between warming attributable to greenhouse gases over the 20th century, the idealised Transient Climate Response (TCR)⁷ to a 1% increasing CO₂, and global mean warming over the 21st century under any sustained increase in forcing scenario (e.g. A1FI, A2, IS92a etc). A range of attribution studies estimate the 20th century attributable greenhouse warming trend to be in the range 0.6-1.3°C/century (5-95% range)^{5,6,7}, taking into account uncertainty in anthropogenic sulphate forcing and response, natural external forcing and internal variability (see figure). If these attribution studies and transfer functions are correct, then the 5-95% range of uncertainty in both TCR and forecasts of 21st century global mean warming under any one of these scenarios is only around a factor of two regardless of the models used or prior opinions of the forecasters⁸. This is almost certainly less than the corresponding range of uncertainty in climate sensitivity. We refer to such forecasts as STAID, or Stable Inference from Data⁴.

STAIID forecasts are not immutable, since new information might cause us to revise our estimates both of past attributable warming (or whatever the constraining observable quantity might be) and the transfer function linking observable to forecast variables (for example, a new class of ocean model might consistently assign a high likelihood to thermohaline collapse in the near future). But such revisions would represent conventional scientific progress, as the current paradigm (that near-term thermohaline collapse is very unlikely) is overturned. Expert judgement is still required to qualify a STAIID forecast with an assessment of our confidence in the assumptions on which the forecast is based. Its role, however, is second-order: judgement does not impact directly on actual forecast likelihoods.

In contrast, if a probabilistic forecast is based simply on the spread of results from a range of climate models, even if these are weighted by some measure of similarity to observations, then the experts' decisions as to which models to include in the initial ensemble have a first-order impact on forecast likelihoods. For example, the figure shows the distribution of 20th century warming trends attributable to greenhouse gases based on a conventional attribution analysis that does not depend on the amplitude of any model's response to greenhouse or any other external forcing. The crosses show the corresponding warming trends inferred from the TCRs of models in the CMIP-2 model inter-comparison, with diamonds enclosing the models used in the headline uncertainty ranges of the TAR. The decision to exclude the highest-response model from the TAR forecast ranges implies a zero chance of an attributable 20th century greenhouse warming trend exceeding 1°C/century, even though the data allows a >30% chance of a past greenhouse warming of this magnitude. We will argue that probabilistic forecasts cannot be considered robust as long as they are so dependent on expert judgment, and the solution is to condition forecasts explicitly on observations, using models to identify useful relationships between observable and forecast variables rather than as an explicit input into the forecast likelihoods themselves.

Comparison of the distribution of transient responses to increasing CO₂ expressed as attributable warming over the 20th century (top axis) and Transient Climate Response, TCR (bottom axis). Crosses indicate members of the CMIP-2 model inter-comparison, while diamonds show models included in the summary figures of the 2001 IPCC Scientific Assessment. Inset panel shows the number of CMIP-2 models falling into each decile of the distribution inferred from the detection and attribution analysis: a representative ensemble would have equal numbers in each decile, whereas a forecast based on this ensemble, even if weighted by distance from observations, would substantially underestimate the likelihood of high TCRs. See ref. 4 for more details.



1. Reilly, J., Stone, P.H., Forest, C.E., Webster, M.D., Jacoby, H.D. and Prinn, R.G. 2001. Uncertainty and climate change assessments. *Science* **293**: 430-433.
2. Allen, M., Raper, S. and Mitchell, J. 2001. Uncertainty in the IPCC's Third Assessment Report. *Science* **293**: 430-433.
3. L. A. Smith. What might we learn from climate forecasts? *Proc. National Academy of Sciences*, **99**:2487-2492, 2002.
4. M. R. Allen, J. A. Kettleborough and D. A. Stainforth, Model error in weather and climate forecasting, in T. N. Palmer (ed.), *Proc. 2002 ECMWF Predictability Seminar*, ECMWF, Reading, UK
5. M. R. Allen, P. A. Stott, J. F. B. Mitchell, R. Schnur, and T. Delworth. Quantifying the uncertainty in forecasts of anthropogenic climate change. *Nature*, **407**:617-620, 2000.
6. P. A. Stott and J. A. Kettleborough. Origins and estimates of uncertainty in predictions of twenty-first century temperature rise. *Nature*, **416**:723-726, 2002.
7. J. T. Houghton, Y. Ding *et al* (eds.). *Climate Change 2001: The Science of Climate Change*. Cambridge University Press, 2001.
8. P. J. Michaels, R. C. Balling and R. C. Balling (Jr.), *The Satanic Gases: Clearing the air about global warming*, Cato Institute, 2000