# OVERSENSITIVE

## HOW THE IPCC HID THE GOOD NEWS ON GLOBAL WARMING

Nicholas Lewis and Marcel Crok

Foreword by Professor Judith Curry

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# Contents

# Foreword

The sensitivity of our climate to increasing concentrations of carbon dioxide is at the heart of the scientific debate on anthropogenic climate change, and also the public debate on the appropriate policy response to increasing carbon dioxide in the atmosphere. Climate sensitivity and estimates of its uncertainty are key inputs into the economic models that drive cost-benefit analyses and estimates of the social cost of carbon.

The complexity and nuances of the issue of climate sensitivity to increasing carbon dioxide are not easily discerned from reading the Summary for Policy Makers of the Assessment Reports undertaken by the Intergovernmental Panel on Climate Change (IPCC). Further, the more detailed discussion of climate sensitivity in the text of the full Working Group I Reports lacks context or an explanation that is easily understood by anyone not actively reading the published literature.

This report by Nic Lewis and Marcel Crok addresses this gap between the IPCC assessments and the primary scientific literature by providing an overview of the different methods for estimating climate sensitivity and a historical perspective on IPCC's assessments of climate sensitivity. The report also provides an independent assessment of the different methods for estimating climate sensitivity and a critique of the IPCC AR4 and AR5 assessments of climate sensitivity. This report emphasizes the point that evidence for low climate sensitivity is piling up. I find this report to be a useful contribution to scientific debate on this topic, as well as an important contribution to the public dialogue and debate on the subject of climate change policy.

I agreed to review this report and write this Foreword since I hold both authors of this report in high regard. I have followed with interest Nic Lewis' emergence as an independent climate scientist and his success in publishing papers in major peer reviewed journals on the topic of climate sensitivity, and I have endeavored to support and publicize his research. I have interacted with Marcel Crok over the years and appreciate his insightful analyses, most recently as a participant in climatedialogue.org.

The collaboration of these two authors in writing this report has resulted in a technically sound, well-organized and readily comprehensible report on the scientific issues surrounding climate sensitivity and the deliberations of the IPCC on this topic.

While writing this Foreword, I considered the very few options available for publishing a report such as this paper by Lewis and Crok. I am appreciative of the GWPF for publishing and publicizing this report. Public accountability of governmental and intergovernmental climate science and policy analysis is enhanced by independent assessments of their conclusions and arguments.

Judith Curry
Atlanta, GA, USA
February 2014

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# About the authors

## Nic Lewis

Nic Lewis is an independent climate scientist. He studied mathematics and physics at Cambridge University, but until about five years ago worked in other fields. Since then he has been researching in climate science and in areas of statistics of relevance to climate science. Over the last few years he has concentrated mainly on the problem of estimating climate sensitivity and related key climate system properties. He has worked with prominent IPCC lead authors on a key paper in the area. He is also sole author of a recent paper that reassessed a climate sensitivity study featured in the IPCC AR4 report, showing that the subjective statistical method it used greatly overstated the risk of climate sensitivity being very high. Both papers are cited and discussed in the IPCC's recently released Fifth Assessment Report.

## Marcel Crok

Marcel Crok is a freelance science writer based in Amsterdam, The Netherlands. He used to work as an editor for *Natuurwetenschap & Techniek*, a Dutch popular science magazine (recently this magazine has become the Dutch edition of *New Scientist*). In 2005 he published a long article about the infamous hockey stick graph, featuring the criticism of Stephen McIntyre and Ross McKitrick. He published a Dutch book about global warming in 2010. After Climategate and the turmoil surrounding the AR4 IPCC report the Dutch government asked him to review the fifth IPCC assessment report as an expert reviewer. With the leading Dutch climate institutes KNMI and PBL, Crok also set up an international discussion platform, climatedialogue.org, which facilitates constructive dialogues between scientists with different views.

## Executive summary

Climate sensitivity is an estimate of how much global warming will result from a doubling of carbon dioxide concentrations, and is a key measure in the climate policy debate.

Previously scientists have estimated climate sensitivity mainly from computer model simulations of the climate system. For the last two generations of models, the value for long-term warming has averaged 3.2°C per doubling. Due to the moderating effect of the ocean, such warming takes many centuries to be fully realised. Over a seventy year period – relevant to warming in the second half of this century – during which carbon dioxide concentrations double, computer climate models show an average temperature rise of around 2°C.

With these values the total warming will cross the iconic two degrees limit later this century – perhaps in only about thirty years under the highest emissions scenario.

Only in recent years has it become possible to make good empirical estimates of climate sensitivity from observational data such as temperature and ocean heat records. These estimates, published in leading scientific journals, point to climate sensitivity per doubling most likely being under 2°C for long-term warming, and under 1.5°C over a seventy-year period. This strongly suggests that climate models display too much sensitivity to carbon dioxide concentrations and in almost all cases exaggerate the likely path of global warming.

Although these new results are reported in the body of the recently-published Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), their impact is not made clear and few readers of the report would learn of them.

In the Fourth Assessment Report of the IPCC, the empirical estimates of climate sensitivity were largely based on poor data and used an inappropriate statistical basis, biasing them towards higher values of climate sensitivity and thus making the global warming problem appear 'worse'. In the recent Fifth Assessment Report, many studies still use inappropriate data and/or statistical methodology.

Between the Fourth and Fifth Assessment Reports the best estimate of the cooling effect of aerosol pollution was greatly reduced. That necessarily implies a substantially lower estimate for climate sensitivity than before. But the new evidence about aerosol cooling is not reflected in the computer climate models. This is one of the reasons that a typical climate model has a substantially higher climate sensitivity than would be expected from observations: if a model didn't have a high climate sensitivity, its excessive aerosol cooling would prevent it matching historical warming.

Good empirical estimates of both long-term warming and that over a seventy-year period now imply very different expectations of future warming than do climate models – some 40% to 50% lower to 2081–2100. This is almost certainly the most important finding of climate science in recent years, particularly since there are good reasons to doubt the reliability of climate model forecasts. However, in its report the IPCC only alludes to this issue in an oblique fashion. Moreover, rather than reducing its best estimate of climate sensitivity in the light of the new empirical estimates, it simply reduced the lower bound of the uncertainty range and omitted to give a best estimate, without adequately explaining why it had been necessary to do so. Only in the final report published in January 2014 was a paragraph added in the Technical Summary giving slightly more explanation.

The new information on climate sensitivity suggests that even with relatively high emissions the government's two-degree limit for global warming is likely to be reached only towards the end of the century.

# Introduction

This report is a reaction to the scientific part (WG1) of the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5). This report focuses on how AR5 dealt with climate sensitivity, a key parameter in global warming policy decisions. Put very simply, if climate sensitivity is high then we can expect substantial warming in the coming century if greenhouse gas emissions are not severely reduced. If climate sensitivity is low, then future warming will be substantially lower, as will the rise in sea level, and the environmental threat posed by carbon dioxide emissions is necessarily smaller.

Climate sensitivity relates changes in surface temperature to changes in the warming influence of greenhouse gases and other agents affecting the Earth's radiation balance. It is defined as the amount of global surface warming that eventually results when the concentration of atmospheric carbon dioxide doubles.[1] The term generally refers to the rise in temperature once the climate system has fully warmed up, a process taking over a thousand years. This long-term measure, termed 'equilibrium climate sensitivity' (ECS), is most widely used. A shorter term measure of sensitivity, transient climate response (TCR), represents the extent of global warming over a 70-year timeframe.

In a very apt 1998 paper Van der Sluijs noted that the concept of climate sensitivity 'acts as an "anchor" that fixes the scientific basis for the climate policy debate'.[2] Not only is it scientifically important but it drives estimates of the economic harm done by global warming and hence directly affects policy decisions.

In the international policy arena, the ultimate, two-decade-old goal is to limit global warming to a level that prevents 'dangerous anthropogenic interference' with the climate. In recent years this has been somewhat arbitrarily defined as preventing warming more than 2°C above preindustrial temperatures. We are already about 0.8°C on the way to this level of warming and have only 1.2°C to go. With a climate sensitivity of 3°C, consistent with climate models, 2°C of warming will very probably be reached later this century, depending mainly on how quickly emissions of greenhouse gases rise.

However, the scientific validity of the two-degree target has been questioned.[3] For example Jaeger (2011) noted that:

> The 2° limit has emerged nearly by chance, and it has evolved in a somewhat contradictory fashion: policy makers have treated it as a scientific finding, scientists as a political issue. It has been presented as a threshold separating a domain of safety from one of catastrophe, and as an optimal strategy balancing costs and benefits.

Tol (2007) concluded that 'this target is supported by rather thin arguments, based on inadequate methods, sloppy reasoning, and selective citation from a very narrow set of studies'.

This report is written for the lay reader, and summarises a longer, more technical document which is available online.[4]

## Unexpected decision in the Fifth Assessment

For over thirty years, international assessments of climate science, including those of the IPCC, have presented an uncertainty range and a best estimate of ECS. In most cases, the uncertainty range has been given as 1.5–4.5°C and the best estimate as 3°C. Only the third assessment report, published in 2001, did not give a best estimate. In the last IPCC report, AR4, the authors raised the low-end of the 'likely' range – the central two-thirds probability – to 2°C. But the AR5 reduced the lower bound back to 1.5°C, in effect admitting that the assessment in AR4 was suspect.

An unanticipated decision in AR5 was that the report did not provide a best estimate for ECS, an omission that readers might have expected to be fully explained and justified in the Summary for Policymakers (SPM) and the accepted version of the full report released a few days after the SPM. However, this was hardly the case. The interested reader was left with a footnote in the SPM, which merely stated that no best estimate could be given 'because of a lack of agreement on values across assessed lines of evidence and studies'. (SPM, footnote 16)

The value of ECS is arguably the most important parameter in climate science, and the decision not to offer any guidance as to whether its best estimate lies towards the bottom, in the middle or towards the top of the 'likely' range was unexpected. To find only a limited explanation and then only in a footnote is rather surprising.

There was, however, some explanation for the reduction in the lower bound of the 'likely' range for climate sensitivity (our emphasis):

> The lower temperature limit of the assessed likely range is thus less than the 2°C in the AR4, but the upper limit is the same. *This assessment reflects improved understanding, the extended temperature record in the atmosphere and ocean, and new estimates of radiative forcing*.[5]

We believe that this paragraph, and in particular the highlighted sentence, reveals why no best estimate was given, but we think that few readers will have noted it. Specifically, new evidence as to the level of climate forcing, combined with the stability of global temperature since the AR4 report, has yielded empirical sensitivity estimates noticeably lower than those of the computer models on which so much of the IPCC report is based. (Forcing is the technical term for the influence of greenhouse gases and other agents on the radiation balance of the climate.) In order to identify a 'best' estimate, the IPCC authors would have had to choose between the data or the models, with potentially embarrassing consequences either way. While we agree with the text as such, we believe the consequences of the 'improved understanding' are more far-reaching than the IPCC AR5 report has let on. In this report we will explain why.

## History of climate sensitivity estimates

A National Academy of Sciences' report in 1979 (the Charney report) is regarded as the first major assessment of climate sensitivity. For most of the period since that time, ECS has been estimated using complex computer simulations of the climate – so-called 'general circulation models' (GCMs). Both the previous generation (CMIP3) of GCMs used for AR4 and the current (CMIP5) GCMs used for AR5 have an average ECS estimated as 3.2°C. Earlier GCMs also had average ECS values of around 3°C.

The range and the best estimate of ECS in official reports over the same period has fairly closely reflected the range and average for the GCMs (see Table 1).

The table also shows the evolution of the range for TCR since it was first given in 2001. TCR is also estimated from GCM simulations and, although the IPCC has never published a best-estimate figure, the average of their estimates is between 1.8°C and 1.9°C per doubling of carbon dioxide concentration.

Van der Sluijs (1998) looked at the reasons why the range for climate sensitivity has changed so little over time while the science has evolved enormously.[6] He concluded that the range was only partly determined by the science itself and that lots of other factors played a role. Among them was 'a need to create and maintain a robust scientific basis' to support policy action.

As this report will make clear, the 1998 historical analysis of Van der Sluijs still applies today. However, we will argue that the scientific evidence supporting a substantial change in both the range and the best estimate for climate sensitivity is now so strong that any serious scientific assessment should describe it in detail.

**Table 1:** Evolution of equilibrium climate sensitivity estimates in the last 35 years and the range for transient climate response since 2001

| | ECS Range (°C) | ECS Best estimate (°C) | TCR Range (°C) |
|---|---|---|---|
| Charney Report 1979 | 1.5–4.5 | 3.0 | |
| NAS Report 1983 | 1.5–4.5 | 3.0 | |
| Villach Conference 1985 | 1.5–4.5 | 3.0 | |
| IPCC First Assessment 1990 | 1.5–4.5 | 2.5 | |
| IPCC Second Assessment 1995 | 1.5–4.5 | 2.5 | |
| IPCC Third Assessment 2001 | 1.5–4.5 | None given | 1.1–3.1[a] |
| IPCC Fourth Assessment 2007 | 2.0–4.5 | 3.0 | 1.0–3.0 |
| IPCC Fifth Assessment 2013 | 1.5–4.5 | None given | 1.0–2.5 |

[a]Range based on models only.

# Observations indicate a low climate sensitivity

As noted above, computer simulations of the climate by GCMs have been the main source of estimates of ECS and TCR. Until nearly the end of the twentieth century, records of factors affecting the climate and of changes in the climate itself were too uncertain to quantify any anthropogenic climate 'signal' above the 'noise' of natural climate variability. However, since that time the signal has become stronger and it has become practicable to derive good estimates of ECS using observational data from the period since 1850, the so-called 'instrumental' period.

## Energy budget estimates of climate sensitivity

The simplest such approach, first described by the UK scientist Jonathan Gregory and colleagues in 2002,[7] relied on a basic physical principle: the conservation of energy.[8] This is a stark contrast to the highly complex and highly uncertain modelling of physics in a GCM, and means that Gregory's so-called 'energy budget' method of estimating climate sensitivity is particularly robust. Energy budget estimates in effect represent a gold standard, provided the observational values and estimates used to construct them are realistic. Note, however, that the Gregory study relied to some extent on computer simulations, mostly because at that time there were no suitable observational estimates of the effects of pollution ('aerosols') on climate; the study was therefore not entirely empirical.

The Gregory et al. best estimate[9] for ECS came out at the very high value of 6.1°C and was presented in a prominent figure in AR4. However, one of this report's authors (Lewis) has since worked his way through the Gregory et al. method and discovered that the ocean heat content (OHC) dataset used was erroneous, and that a surprisingly small change in forcing was used.[10] When suitable corrections and different forcing data were applied, the new ECS estimate was only 1.8°C, and the result was much better constrained.

## How the Fourth Assessment got its sensitivity estimate wrong

Before discussing how climate sensitivity was treated in the AR5 report, it is useful first to discuss how the subject was presented in the fourth IPCC report, published in 2007. Figure 9.20 in AR4 WGI described a range of estimates of ECS using so-called probability density functions (PDFs). These PDFs are replicated in Figure 1. Each curve represents a separate estimate, with the position of the peak representing the most likely value[11] of ECS and the shape of the curve representing the uncertainty in that estimate. For example, good estimates will have tall, narrow peaks, while uncertain ones will have low wide ones.

The graph shows eight observationally-based ECS studies (one of these was based on palaeoclimate data – see below – rather than instrumental observations). The dotted black line is our addition to those appearing in the original Figure 9.20. We will comment briefly on the various studies to which these PDFs relate.

Most of the studies have identifiable methodological and/or data shortcomings. The shortcomings in the Gregory et al. (2002) estimate have already been discussed. The PDF of Hegerl et al. (2006), a palaeoclimate study, is so broad as to provide almost no useful information about the value of ECS. Likewise Knutti et al. (2002) did not provide any useful constraint and the results were also biased upwards by use of the same erroneous OHC dataset as Gregory et al. (2002).

Most of the studies adopted a Bayesian statistical approach. In Bayesian analysis, rather than simply calculating a result, a starting position (the 'prior') is updated based on new data. The Bayesian approach is well suited to dealing with uncertain parameters and its use is not particularly controversial. But readers

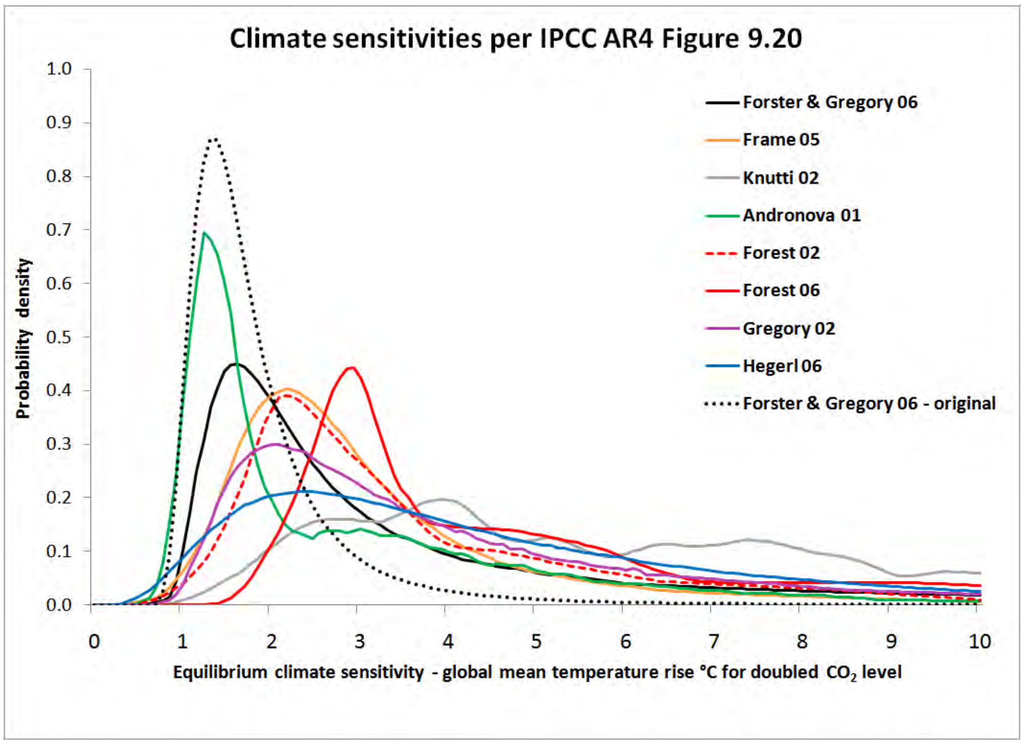


**Figure 1:** Replication of PDFs from Figure 9.20 in AR4 WGI

The dotted black line is an addition to those appearing in Figure 9.20 and shows the original results of Forster/Gregory (2006). All PDFs were scaled in AR4 to allocate all probability (one in total) between 0°C and 10°C.

of scientific reports based on Bayesian analysis can easily overlook the fact that the choice of prior can significantly affect the result. If the chosen prior is itself controversial, this sharply downgrades the robustness of any findings.

Although the design of scientific studies may be informed by existing knowledge, once designed it is normal for their results only to reflect knowledge gained from the data used. Therefore, it is necessary for the prior estimate properly to represent, in mathematical terms, ignorance about climate sensitivity, not what the researcher believes about it before seeing the new data. In other words, the prior should be chosen to have minimal influence on the resulting ECS estimate: it should let the data 'speak for themselves'. Hardly any of the priors used in AR4 and AR5 satisfied this requirement.

Of the studies underlying the PDFs in Figure 1, five (Knutti et al., Hegerl et al. and three others) used priors that were scientifically controversial and strongly biased their ECS estimates upwards. In addition, one of these other studies[12] was affected by statistical errors and poor experimental design, another [13] used erroneous OHC change data, and a third was affected by both these errors.[14] Still another study[15] had unrealistic input assumptions and also appears to have been affected by an error in its computer code that substantially biased upwards its estimate for ECS.[16]

Only one ECS study featured in AR4 stands out as being free of these defects: Forster and Gregory (2006). Unlike all the other instrumental studies, it derived an estimate that was almost fully based on observations, and it did not have evident flaws such as faulty data or methodology. The authors did not use the energy budget approach, but instead used satellite measurements of changes in radiation at the top of the atmosphere and related those to changes in the global temperature. This gave them a direct estimate of climate sensitivity, with little dependence on changes in aerosols, the most important source of uncertainty in energy budget and computer simulation estimates. In their original paper their results were fairly tightly constrained, meaning that the range of possible values for climate sensitivity was limited. Their best estimate was 1.6°C.

However, in AR4 the IPCC misrepresented the Forster and Gregory results by restating them on the same inappropriate Bayesian statistical basis that had biased most of the other studies.[17] The IPCC's version of the Forster and Gregory curve (the solid black line in Figure 1) has a peak skewed substantially to higher climate sensitivities and also the tail is much 'fatter' – in other words the probabilities of high sensitivities are relatively greater – than in the original results, which are shown in Figure 1 by the dotted black line. This misrepresentation[18] was highly consequential, since it involved the only good-quality evidence that was nearly independent of the GCMs, and the alteration substantially increased the apparent risk of high future warming.

The message here is clear. AR4, published in 2007, could already have concluded from the instrumental data that climate sensitivity might well be lower than the 2°C lower limit that GCMs continued to suggest. But instead the IPCC AR4 authors actually *raised* the lower bound of the likely range for climate sensitivity from 1.5°C to 2°C, while retaining a best estimate of 3°C. Note that the best estimate from the Forster and Gregory (2006) paper (1.6°C) fell outside this likely range.

## The good news in the Fifth Assessment

Aerosols are – by their cooling effect on the climate – thought to have counteracted some of the warming from greenhouse gases. The effect of aerosols is the biggest uncertainty in estimates of total anthropogenic forcing. Knowledge about aerosols is therefore of crucial importance for estimates of climate sensitivity.

And this is where the AR5 report has some excellent news. AR5 revises downwards the estimated cooling effect (forcing) of aerosols markedly compared to AR4. This is, perhaps counterintuitively, good news. The observed temperature increase to date could result from a high climate sensitivity combined with a large aerosol cooling effect or a low sensitivity combined with a small aerosol cooling effect (or combinations in between these extremes). Therefore, to the extent that aerosol forcing is small, sensitivity to carbon dioxide concentrations must also be relatively low.

Since AR4 the best estimate of aerosol forcing has come down substantially. This is purely a matter of what the IPCC has called 'improved understanding'. In addition, greenhouse gas concentrations have increased, but global temperatures have hardly changed. The effect on climate sensitivity is that estimates of TCR should now be approaching 30% lower.

If we dig a little deeper into the full AR5 report the news gets even better. The best estimate the IPCC gives for total aerosol forcing is not fully based on observations. It is a composite of estimates derived from simulations by global climate models and from satellite observations. On their own, the satellite observation estimates are lower, suggesting that observationally-based TCR estimates should arguably be lower still.

When all this new data is put together, it is possible to prepare new estimates for ECS and TCR using the robust energy budget method of Gregory et al. with AR5 forcing and OHC data. The details of this calculation are given in the technical version of this report.[4] The ECS best estimate is 1.7°C, which is very close to the IPCC's lower bound of 1.5°C, and much lower than per the GCMs (average 3.2°C, best estimate 2.9°C). The TCR best estimate is 1.3°C which is likewise close to the IPCC's lower bound of 1°C, and much lower than the average GCM estimate of between 1.8°C and 1.9°C.

## Evidence for low climate sensitivity piling up

Recently several studies estimating ECS have been published in the peer reviewed literature based on data from the instrumental period and methodology that appears satisfactory, and which in particular incorporate observationally based aerosol forcing estimates.[19] One of us (Lewis) was sole author of one of those studies, which is cited in several places in AR5 WGI. He is also a co-author of the Otto et al. (2013) study. That study is notable because almost all of its other fifteen co-authors are also lead or coordinating lead authors of those chapters of the AR5 WGI report that are relevant to the question of climate sensitivity.

In his own study Lewis comes up with a best estimate for climate sensitivity of 1.6°C, with a 'likely' range of 1.3–2.2°C.[20] The Otto et al. study reaches a slightly higher sensitivity of 2.0°C,[21] with a 'likely' range of 1.5–2.8°C.

These four studies were published in time to be included in AR5. All of them find best estimates for climate sensitivity of between 1.6°C and 2°C. See Table 2 for these best estimates and likely ranges. The table also shows the corresponding estimates and ranges given as the overall assessments both in AR4 and AR5, and for the sets of climate models used in AR4 and AR5.

Otto et al. provided two main estimates. Their primary estimate used data from 2000–2009, while the main alternative set of results used data over the 40-year period 1970–2009. In fact, the best estimates based on data for just the 1980s and just the 1990s are very similar to those based on data for 1970–2009, which demonstrates the robustness of the energy budget method.

All these observational studies, except Aldrin et al. (2012), used objective statistical methods, avoiding the problems of inappropriate Bayesian methodology and the resulting bias that afflicted many of the observational studies featured in AR4 and AR5. Aldrin et al. (2012) also gave alternative results using what appears to be a more objective Bayesian 'prior' for ECS: that best estimate for ECS was 1.53°C, with a likely range of 1.2–2.0°C.

### Heat going into the oceans

Around the initial publication of the AR5 report in late September, media attention focused on what has been dubbed the 'hiatus' in global warming: the

**Table 2:** Recent empirical estimates for ECS that incorporate observationally-based aerosol forcing estimates, compared with those from models and in IPCC reports

| Study | Best estimate (°C) | Likely range (°C) |
|---|---|---|
| Ring et al. 2012 (using 4 surface temperature datasets) | 1.80 | 1.4–2.0 |
| Aldrin et al. 2012 (main results) | 1.76 | 1.3–2.5 |
| Lewis 2013 (preferred main results[20]) | 1.64 | 1.3–2.2 |
| Otto et al. 2013 (2000s data) | 2.00 | 1.5–2.8 |
| Otto et al. 2013 (1970–2009 data) | 1.91 | 1.3–3.0 |
| Average of the above[a] | 1.79 | 1.3–2.4 |
| CMIP3 models (per AR4 Table 8.2) | 3.20 | 2.1–4.4 |
| CMIP5 models (per AR5 Table 9.5) | 2.89 | 1.9–4.5 |
| IPCC AR4 2007 | 3 | 2.0–4.5 |
| IPCC AR5 | None given | 1.5–4.5 |

[a]Giving a 50% weight to each of the two Otto 2013 estimates.

fact that the global temperature has barely risen for 15 years. Several explanations have been put forward, a favourite one being that heat accumulation has continued in the ocean – indeed that it has accelerated since about 2000 – and that you cannot say therefore that the warming of the climate has stopped.

However, recent studies like Otto et al. (2013) take a higher recent heat inflow into the oceans into account. So although more heat going into the oceans – which is contradicted by some datasets – might be an explanation for the slowdown of the warming at the surface, it does not materially change our recent estimates for ECS. They are still far lower than the best estimate of 3°C that has been around for thirty years. The hiatus does, however, decrease estimates for TCR, which is thought to be more policy relevant.

## A new 'best observational' estimate of climate sensitivity

A new 'best observational' estimate of ECS can now be calculated by taking a simple average of the different observationally-based estimates in Table 2. This gives[22] a best estimate for ECS of 1.75°C and a likely range of about 1.3–2.4°C. However, recognising that error and uncertainty may be greater than allowed for in the underlying studies, and will predominantly affect the upper bound of the range, we conservatively assess the likely range as 1.25–3.0°C.

Now compare these figures with those in AR4 and AR5 (see also Table 1 for the longer historical evolution of the range). Our new 'best observational' ECS estimate of 1.75°C is more than 40% lower than both the best estimate in AR4 of 3°C and the 3.2°C average of GCMs used in AR5. At least as importantly, the top of the likely range for ECS of 3.0°C is a third lower than that given in AR5 (4.5°C) – even after making it much more conservative than is implied by averaging the ranges for each of the observational estimates. Note also that the best observational estimate is close to the value of 1.7°C we gave above using the most up-to-date data and the method of Gregory et al.

## Poor estimates obscure the issue

Of course, the four studies included in Table 2 represent only a part of one line of evidence cited in AR5 as to the value of ECS. In AR5, the IPCC showed ranges from many sources, categorised by line of evidence (reproduced below as Figure 2). Examination of this figure shows the 'lack of agreement' between lines of evidence that was mentioned in a footnote in the Summary for Policymakers.

The AR5 authors might not have wanted to declare that some studies are better than others or to adjudicate between observational and model-based lines of evidence, but we believe that this is exactly what an assessment is all about: using expert knowledge to weigh different sources of evidence. In this section we present reasoned arguments for a different assessment to that in AR5.

We will therefore discuss the estimates in Figure 2 in some detail, showing why little weight should be put on the estimates that conflict with the 'likely' ranges for the best observational studies in our Table 2, either because of some identified serious shortcoming in their derivation or on the basis that they use a method upon which AR5 itself casts doubt.

### Instrumental estimates

The unlabelled ranges in Figure 2 are for studies cited in AR4. As explained above, these are all, with one exception, unsatisfactory. The exception is the original Forster and Gregory (2006) range (the unlabelled solid mauve bar,

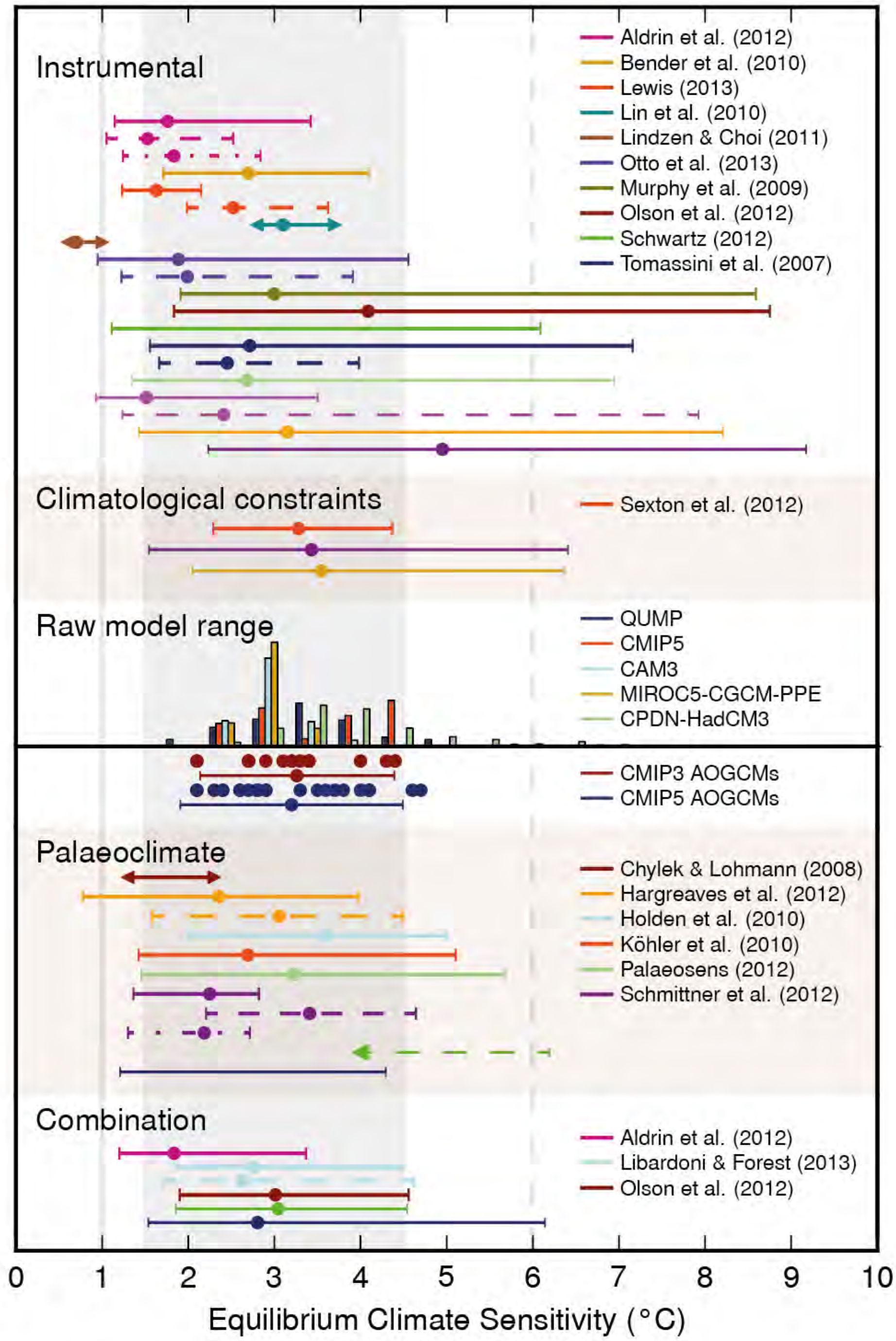


**Figure 2:** ECS estimates categorised by line of evidence

The figure is a reproduction of Box 12.2, Figure 1 from AR5. Bars show 5–95% uncertainty ranges for ECS, with the best estimates marked by dots. Actual ECS values are given for CMIP3 and CMIP5 AOGCMs. Unlabelled ranges relate to studies cited in AR4.

fourth up from the bottom of the Instrumental section in Figure 2), which is closely consistent with the 'Average' range in Table 2.

The labelled ranges in Figure 2 are the studies that were new in AR5. Some have already been discussed in relation to our Table 2 above. The other AR5 studies are all unsatisfactory. Some are based on methods that the IPCC itself suggests are unsatisfactory:[23] climate response to volcanic eruptions[24] or short-term measurements from satellites.[25] The remaining studies[26] also have identified shortcomings that we believe make their estimates of ECS unsatisfactory (see Appendix to the technical version of this report).

## Climatological constraints

Climatological constraint studies combine computer simulations and instrumental data. However, the estimates shown in Figure 2 are all based on the Met Office's HadCM3 climate model, which is known to be inappropriate for use in this kind of study.[27,28] Moreover, the instrumental data used provides no information about climate change. The climatological constraint studies shown are therefore of little or no value as estimates of ECS.

## Conflict between models and observations: raw model range

As the conflict between observational and GCM estimates of ECS is a central issue, and AR5 also cites a related line of evidence referred to as feedback analysis (the analysis of feedbacks simulated by GCMs), it is appropriate to discuss in some detail feedbacks and ECS in climate models.

It is almost universally accepted that by itself the equilibrium warming effect of a doubling of the carbon dioxide concentration is slightly more than 1°C. Why then do models have an average ECS of 3°C? This is due to the knock-on effects of the initial warming: so-called 'positive feedbacks'. Combined with the initial warming, three feedbacks – water vapour, lapse rate and albedo – can together explain an ECS value of 2°C. The remaining 1°C required to explain the GCM average of 3°C is accounted for primarily by cloud feedback and related adjustments.

But clouds are a big headache for the modellers. It is very difficult to simulate them at all, let alone to predict how they will change in the future. Observational evidence for a positive cloud feedback is weak, at best,[29] so on these grounds, GCM estimates of climate sensitivity are highly questionable.

A second concern is that there is no knob for climate sensitivity as such in global climate models. Instead there are many adjustable parameters affecting the treatment of processes (such as those involving clouds) that GCMs do not calculate from basic physics. Whether these parameterisations are sufficiently accurate, and include all important processes, is very much open to question.

Climate scientists tend to assume that their models produce realistic estimates of climate sensitivity if they produce simulated climates that match observations over the instrumental period. However, there is no scientific basis for this assumption. An experienced team of climate modellers has written that models can be made to match observations in many different ways, each with substantially different climate sensitivities.[30] They also say that good matching between GCM simulations and observations of global temperatures – a very common test, cited approvingly in the AR4 report as proving model skill – actually proves little.

A lot of the recent public attention has been focussed on the slowdown of global warming in the last 15 years, which the climate models failed to predict. Defenders of the models tend to admit that models have difficulties with natural fluctuations in the climate that last for 10 to 15 years. However, the situation is much worse. Virtually all the models that the IPCC uses in its report have been running too hot over the last 35 years as well, long enough to judge them on a climatic time scale:[31] see Figure 3 below.

If there were broad agreement between GCMs as to the sign and – within, say, a factor of two – the magnitude of all significant feedbacks and other factors of relevance, then it would be reasonable to place significant weight on GCM-based evidence about climate sensitivity. However, despite model development being closely informed by diverse observations, that is not the case. So we think one should disregard GCM-based evidence about climate sensitivity – everything shown in the 'Raw model range' section of Figure 2. This is not only because of the uncertainties over how the models represent the climate, but also because, being only tenuously grounded in observations, it is unclear to what extent raw model ECS values qualify as scientific evidence at all.

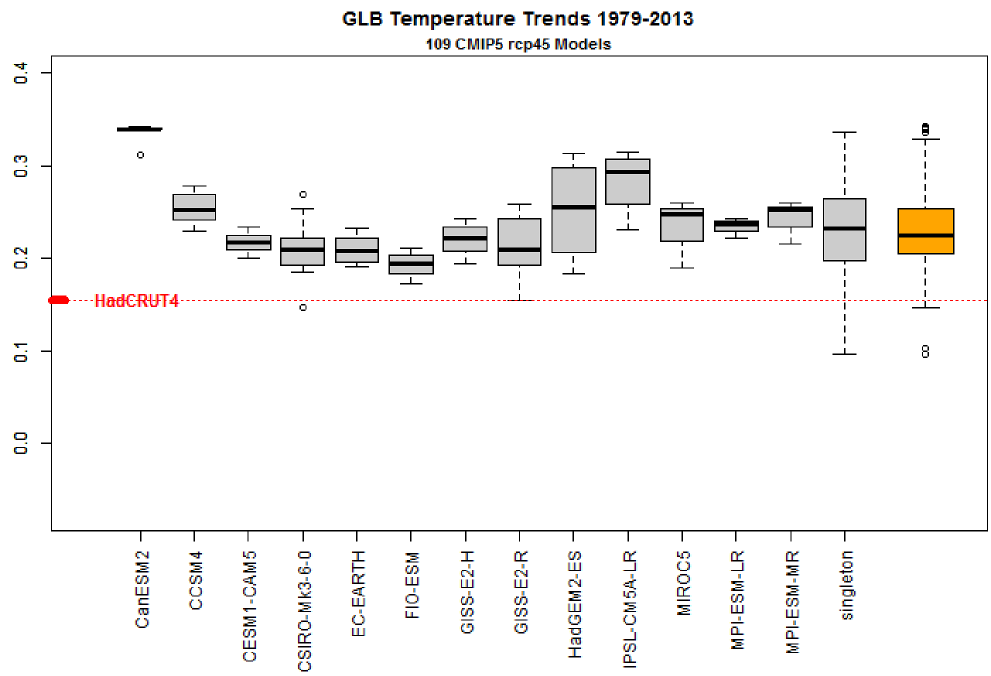


**Figure 3:** Modelled versus observed decadal global surface temperature trend 1979–2013

Temperature trends in °C/decade. Virtually all model climates warmed much faster than the real climate over the last 35 years. Source: http://climateaudit.org/2013/09/24/two-minutes-to-midnight/. Models with multiple runs have separate boxplots; models with single runs are grouped together in the boxplot marked 'singleton'. The orange boxplot at the right combines all model runs together. The default settings in the R boxplot function have been used; the end of the boxes represent the 25th and 75th percentiles. The red dotted line shows the actual trend in global surface temperature over the same period per the HadCRUT4 observational dataset.

## Palaeoclimate

Palaeoclimate studies estimate climate sensitivity by using the proxy climate records of the more distant past (for example, the last millennium, the last ice age, or even longer periods). However, in 2007 the AR4 report concluded that uncertainties in studies based on changes in climate since the last glacial maximum were large. Whilst AR4 did include a range from a last-millennium palaeoclimate study, it only constrained ECS very weakly.[32]

AR5 also discussed palaeoclimate estimates, noting that the results were still only weakly constrained, and suggesting that true uncertainties were likely larger still.[33] With such wide uncertainty ranges, palaeoclimate ECS estimates contain little information. Moreover, AR5 concluded that palaeoclimate ECS estimates based on past climate states very different from today may not be representative of the current state of the climate system. That applies to all the palaeoclimate estimates in Figure 2.

Accordingly, little weight can be put on the palaeoclimate estimates.

## Combination

These are studies based on combining estimates based on different methods. Of the studies cited by the IPCC, the Libardoni and Forest (2013) and Olson et al. (2012) papers, and the unlabelled AR4 studies, have serious shortcomings and their combination estimates of ECS are unsatisfactory (see Appendix to the technical version of this report).[4]

## Instrumental estimates are superior

So, to conclude, we think that of the three main approaches for estimating ECS available today (instrumental observations, palaeoclimate observations, GCM simulations), instrumental estimates – in particular those based on warming over an extended period – are superior by far. Our view as to which type of observational estimates are best is strongly supported by Chapter 12 of AR5 itself.[34]

Among the instrumental period warming based estimates cited in AR5, we have identified several that have substantial shortcomings. This leaves as satisfactory only the ones cited in Table 2 above, which imply a best estimate for ECS of 1.6–2.0°C. That is consistent with our calculations of what AR5's own best estimates for changes in forcing and OHC imply about ECS. On our reading of AR5, the IPCC scientists largely agreed with our analysis of the observational evidence about ECS.

The conflict between the best observational estimates of ECS and the values derived from computer models must have presented the IPCC authors with a dilemma. Large parts of the IPCC reports are built around the computer simulations. Almost all the projections of future climate change are based on them, and a complete chapter is devoted to the performance of the GCMs. Stating that the best observational estimates of ECS now indicate a value for ECS of only 1.5–2°C would come very close to an admission that most of the global climate models substantially overestimate ECS and, by implication, that policymakers should not place reliance on GCM-based projections of our future climate.[35]

It appears that the IPCC authors may have decided to resolve this dilemma by reducing the lower bound of ECS to 1.5°C and not giving a best estimate for ECS. By doing this they went some way to reflect the new, lower estimates that have been published recently in the literature. Now of course the IPCC scientists are quite entitled to reach a different conclusion from us as to how much weight should be placed on GCM-based estimates. However, they failed to discuss this issue clearly in the Summary for Policymakers or in the version of the full WGI report released when the SPM was approved in September 2013.

In the final report published in January 2014 a paragraph was inserted into the Technical Summary discussing the fact that no best estimate for ECS can now be given.[36] This is quite surprising. Edits at this very late stage are meant to correct errors,[37] but the new wording about ECS did not represent the correction of an error; it was just new text. The new paragraph, revealed long after governments approved the SPM, says this:

> In contrast to AR4, no best estimate for ECS is given because of a lack of agreement on the best estimate across lines of evidence and studies and an improved understanding of the uncertainties in estimates based on the observed warming. Climate models with ECS values in the upper part of the likely range show very good agreement with observed climatology, whereas estimates derived from observed climate change tend to best fit the observed surface and ocean warming for ECS values in the lower part of the likely range. In estimates based on the observed warming the most likely value is sensitive to observational and model uncertainties, internal climate variability and to assumptions about the prior distribution of ECS. In addition, 'best estimate' and 'most likely value' are defined in various ways in different studies.

So here AR5 finally gives some additional explanations. The reader could, however, be wrong-footed by the remark that climate models (GCMs) with high ECS values are in good agreement with 'observed climatology'. This simply means they simulate certain properties of the current climate quite well; it does not mean they simulate global warming well. The authors then caveat the observational estimates by mentioning various issues that, where significant, are normally taken account of in sound studies.

A better approach would have been to give two 'best' estimates and ranges for ECS: one derived from the observational studies and one based on the GCMs. This would have alerted policymakers to the divergence between the two and the necessity for, in effect, placing one's bets on the models or the data. We recommended such an approach in our comments in the official review of the draft report but the IPCC did not take up our suggestion.

## What will the future bring?

### Transient climate response in the Fifth Assessment

We now consider what effect the changes in greenhouse gas concentrations might have on global temperatures over the rest of the century. In order to do this, we need first to discuss the IPCC's scenarios for greenhouse gas emissions and then consider how it represented TCR in AR5.

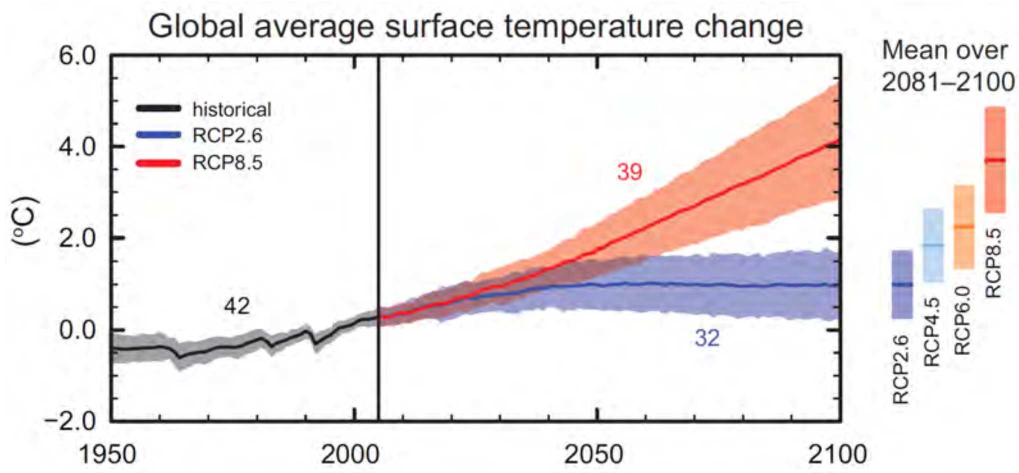


**Figure 4:** Projected global temperature changes over the rest of the century

Reproduced from AR5, Figure SPM.7. Temperature changes are from the 1986–2005 mean, which was 0.6°C above preindustrial (taken as the 1850–1900 mean global surface temperature). The figures denote the number of models involved.

The AR5 report presented, in the Summary for Policymakers, projections for global surface temperature increase through to 2100 based on four scenarios of future greenhouse gas emissions and hence concentrations. These projections are based on simulations by the GCMs. Figure 4 shows (reproduced from

Figure SPM.7) the projections for two of the scenarios. RCP8.5 has the highest greenhouse gas concentrations and consequent warming and RCP2.6 the lowest. Recent increases in greenhouse gas concentrations have been close to those in the middle two scenarios, RCP4.5 and RCP6.0,[38] although emissions appear to have been increasing at a rate at or above that per the RCP8.5 scenario.

So far we have discussed mainly the scientific evidence for estimates of ECS. However, over the next century, TCR is a more relevant measure (except for sea level rise).

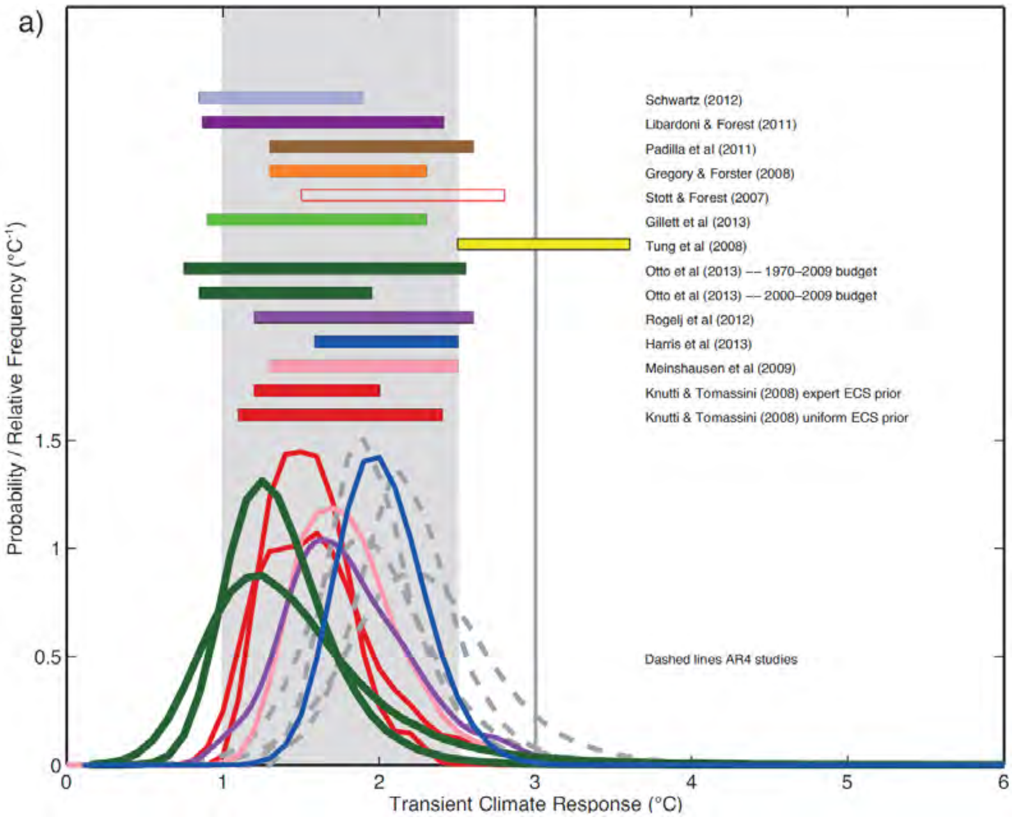


**Figure 5:** Transient climate response distributions estimated from observational constraints

Reproduced from AR5, Figure 10.20(a). Bars show 5–95% uncertainty ranges for TCR.

AR5 showed in its Figure 10.20(a), reproduced here as Figure 5, a range of observationally based TCR estimates. One of us (Lewis) has written a critical analysis of many of these TCR studies.[39] It finds serious fault with most of them. The exceptions – Gillett et al. (2013), Otto et al. (2013) and Schwartz (2012)

– all had relatively low TCRs, the best estimates from each being in the range 1.3–1.4°C.[40] As mentioned earlier in this report, an observationally-based best estimate for TCR of 1.3°C can also be derived from data in AR5 (see page 16). There is a detailed discussion of that estimate and of the observational TCR estimates cited in Figure 10.20(a) of AR5 in a blog post at *Climate Audit*.[41]

In AR5 the IPCC gave the 'likely' range for TCR as 1–2.5°C, and said that it was 'extremely unlikely' to exceed 3°C. This assessment represented only a marginal reduction compared with AR4. No best estimate for TCR was given in either report, but a best observational estimate of 1.4°C can be derived from information in the Summary for Policymakers about anthropogenic changes over 1950–2011, a well-observed period (see the technical version of this report for details[4]).

All the good-quality observational evidence cited supports a best estimate for TCR of between 1.3 and 1.4°C,[42] and we suggest that the most appropriate figure is therefore 1.35°C, with a conservative 'likely' range being 1–2°C. By contrast, GCM estimates of TCR are on average 35% higher at 1.8°C or so, with the TCR for particularly sensitive models substantially higher even than that. For example the UK Met Office HadGEM2-ES model has a TCR of 2.5°C. Figure 6 compares the best empirical estimate for TCR with the TCR values of the 30 climate models covered in AR5.

Figure 6 below shows an evident mismatch between the observational best estimate and the model range. Nevertheless, AR5 states (Box 12.2) that:

> …the ranges of TCR estimated from the observed warming and from AOGCMs agree well, increasing our confidence in the assessment of uncertainties in projections over the 21st century.

How can this be a fair conclusion, when the average model TCR is 35% higher than an observationally-based best estimate of 1.35°C, and almost half the models have TCRs 50% or more above that level? The IPCC obscured this large discrepancy between 'models' and 'observations' by not showing a graph like our Figure 6 and by a misleading statement in the full report.[41]

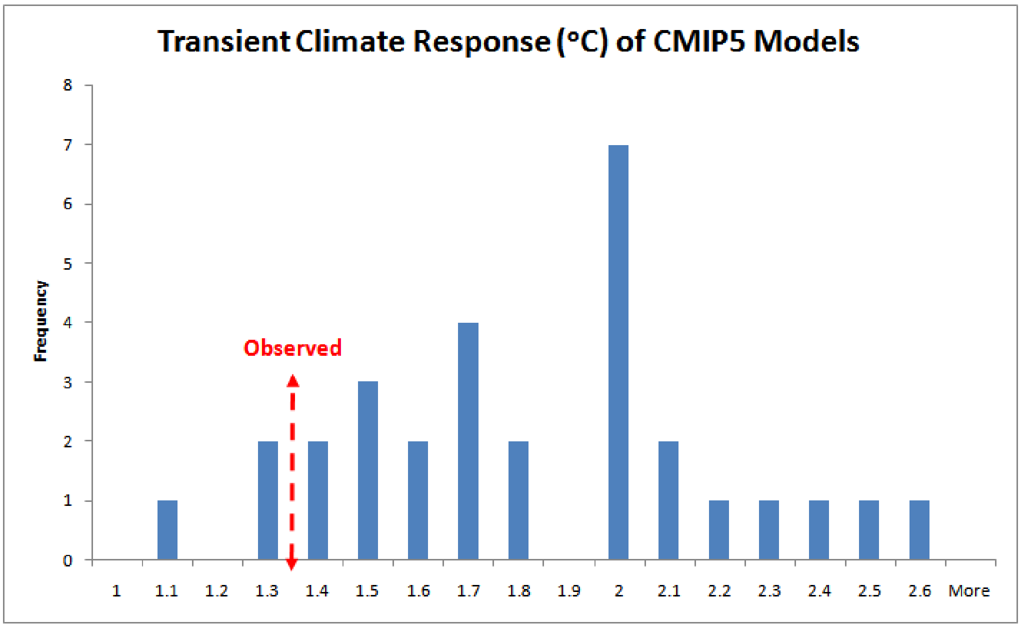


**Figure 6:** Transient climate response distribution for CMIP5 models

Models per AR5 Table 9.5. The bar heights show how many models in Table 9.5 exhibit each level of TCR.

## Warming at the end of the century

As we will show, the mean CMIP5 projected warming to 2081–2100 is far above warming projected using the 'best observational' estimate for TCR we derived earlier.[43] In Table 3 we show for each scenario the amount of warming projected in AR5 up to 2081– 2100, based on the different scenarios that the IPCC uses, from a baseline of 1850–1900 and also from 2012 (after deducting actual warming from 1850–1900 to 2012). The first two columns show the average warming projected by the CMIP5 climate models. The next two columns show the warming based on the best observational estimate for TCR of 1.35 °C. These numbers scale the TCR estimate pro rata to the projected increase in total forcing from 2012 until 2081–2100 on each scenario and then add an allowance for currently unrealised warming from past greenhouse gas increases, plus where relevant the amount of warming up to 2012. The rightmost column shows the ratio of CMIP5-model to observational-TCR based warming from 2012.

The GCMs overestimate future warming by 1.7–2 times relative to an estimate based on the best observational evidence.[44] On the RCP6.0 scenario and using the observational TCR-based method, total warming in 2081–2100 would

**Table 3:** Global warming up to the late twenty-first century

| Scenario | Warming in 2081–2100 based on: CMIP5 models °C | °C | TCR of 1.35°C °C | °C | CMIP5/TCR warming from |
|---|---|---|---|---|---|
| Baseline | 1850–1900 | 2012* | 1850–1900* | 2012 | 2012 |
| RCP2.6 | 1.6 | 0.8 | 1.0 | 0.2 | 3.4× |
| RCP4.5 | 2.4 | 1.6 | 1.6 | 0.8 | 2.0× |
| RCP6.0 | 2.8 | 2.0 | 2.0 | 1.2 | 1.7× |
| RCP8.5 | 4.3 | 3.5 | 2.9 | 2.1 | 1.7× |

*To minimise rounding discrepancies, 0.8°C has been deducted from the CMIP5 global mean surface temperature projected warming from 1850–1900 (taken as representing preindustrial conditions) to obtain warming from 2012, and 0.8°C added to the warming based on TCR from 2012 to obtain warming from 1850–1900. But the unrounded 0.76°C temperature rise from 1850–1900 to 2012 per HadCRUT4 has been used to compute the ratios of CMIP5 model to TCR-based warming.

still be around the international target of 2°C, with a rise of 1.2°C from 2012 rather than the 2°C rise projected by the GCMs. With nearly a century before the target is likely to be breached, policymakers might well conclude that a different policy response was warranted.

# Conclusions

In this report we have shown that the AR4 report in 2007 misrepresented an important observational estimate for climate sensitivity, suggesting a higher value than the original research indicated and thus making the climate change problem seem 'worse'. Perhaps more importantly, it suggests that IPCC authors did not have an adequate grasp of the Bayesian statistical methods used in estimating climate sensitivity.

In the recently released AR5 report the IPCC had the chance to bring readers some good news: the highest quality observational evidence, directly reflecting or consistent with the substantially lower estimate of cooling by aerosol pollution in AR5 than that in AR4, indicates that climate sensitivity is probably below the lower bound set in the AR4 report. However, as we have shown, the IPCC did not explain this fact in clear terms.

We believe that, due largely to the constraints the climate model-orientated IPCC process imposed, the Fifth Assessment Report failed to provide an adequate assessment of climate sensitivity – either ECS or TCR – arguably the most important parameters in the climate discussion. In particular, it did not draw out the divergence that has emerged between ECS and TCR estimates based on the best observational evidence and those embodied in GCMs. Policymakers have thus been inadequately informed about the state of the science.

## Acknowledgements

The authors are very grateful for the help and comments they have received from Dr James Annan, Professor Judith Curry, Professor David Henderson, Professor Ross McKitrick and Andrew Montford.

# Notes

[1]The warming effect of atmospheric carbon dioxide is logarithmic, so each doubling in concentration causes the same temperature increase whatever the starting level.

[2]Van der Sluijs et al. (1998).

[3]Jaeger and Jaeger (2010); Tol (2007).

[4]http://www.thegwpf.org/?p=18296.

[5]AR5, SPM, D.2.

[6]Van der Sluijs et al. (1998).

[7]Gregory et al. (2002).

[8]For further details and discussion see the technical version of the report.

[9]Median: the value at which the estimate is equally likely to be too low or two high. All the best estimates given for ECS and TCR are medians.

[10]http://judithcurry.com/2011/07/07/climate-sensitivity-follow-up/.

[11]The mode: for a skewed PDF this differs from the median, particularly when the peak is wide, and should not be regarded as the best estimate.

[12]Forest et al. (2006).

[13]Frame et al. (2005).

[14]Forest et al. (2002).

[15]Andronova and Schlesinger (2001).

[16]See Ring et al. (2012).

[17]A uniform prior in ECS.

[18]The IPCC does not accept that the restatement amounts to an 'error', on the grounds that the alteration of the Forster and Gregory (2006) PDF (although not its effect) was disclosed and is permissible under a subjective Bayesian philosophy (under which probability has no objective meaning). However, from a scientific viewpoint the altered statistical basis is indefensible.

[19]Aldrin et al. (2012), Ring et al. (2012), Lewis (2013) and Otto et al. (2013).

[20]With non-aerosol forcing and observational surface temperature uncertainties incorporated.

[21]Using data from the most recent decade considered, 2000–09, which arguably should provide the most reliable results. The Otto et al. study could have obtained a lower climate sensitivity best estimate had it used a different source of recent heat uptake data. See http://bishophill.squarespace.com/blog/2013/5/19/new-energy-budget-derived-estimates-of-climate-sensitivity-a.html. Using the heat uptake estimate from Loeb et al. (2012) would have resulted in a best estimate for ECS of 1.7°C, reducing to 1.6°C if the 2000–09 period were extended to 2012.

[22]Based on the estimate for Aldrin et al. (2012) using the more objective prior, marginally rounding up the resulting average best estimate, and excluding the non-probabilistic Ring et al. (2012) range (being the lowest and highest of its four best estimates).

[23]Sections 10.8.2.2 and 10.8.2.3 of AR5 give detailed reasons for doubting the usefulness of ECS estimates based on these methods.

[24]Bender et al. (2010).

[25]Lindzen and Choi (2011) and Murphy et al. (2009).

[26]Lin et al. (2010), Olson et al. (2012), Schwartz (2012) and Tomassini et al. (2007). In the case of Schwartz (2012) the criticism relates only to the section of its range for ECS that exceeds 3 °C.

[27]Due to structural rigidities in the HadCM3 model, no matter what parameter combination is used, when low ECS values are achieved by the model, its aerosol forcing becomes very highly negative – a combination ruled out by the observational data. The Sexton study was unable to investigate the combination of low-to-moderate ECS and low-to-moderately negative aerosol forcing – the region favoured by the observational data. It is thus unsurprising that the study rules out low ECS values. See Box 1 in: http://niclewis.files.wordpress.com/2013/09/metoffice_response2g.pdf. The Sexton et al. (2012) study is identical to the first stages of the Harris et al. (2013) study that it discusses, and the Harris et al. near-final posterior region in the Box 1 Figure B.1 corresponds to the final results of the Sexton et al. (2012) study.

[28]In addition the two unlabelled AR4 studies both barely sampled ECS values below 2 °C at any level of aerosol forcing.

[29]Section 7.2.5.7 of AR5.

[30]Forest et al. (2008).

[31]Several commentators have shown this recently, e.g. http://climateaudit.org/2013/09/24/two-minutes-to-midnight/, http://rankexploits.com/musings/2013/leaked-spm-ar5-multi-decadal-trends/ and http://rogerpielkejr.blogspot.nl/2013/09/global-temperature-trends-and-ipcc.html. A recent commentary in *Nature Climate Change* by Fyfe et al. (2013) reached similar conclusions.

[32]Hegerl et al. (2006). As discussed above, this study used an inappropriate uniform prior for ECS, biasing its ECS estimate upwards.

[33]Discussing the Paleosens Members (2012) review article.

[34]Section 12.5.3.

[35]Projected future warming in GCMs is strongly correlated with ECS, although it increases less than proportionally with ECS due to the moderating effect of heat uptake by the ocean. Projected warming in GCMs could conceivably be in line with observational evidence despite their ECS not being so, but it is not.

[36]The IPCC provided a long list of substantive edits made after the final draft of the report: http://www.ipcc.ch/report/ar5/wg1/docs/review/WG1AR5_SubstantiveEditsList_All_Final.pdf.

[37]The front sheet to the accepted final draft of the AR5 WGI report published on 30 September 2013 stated: ‘Before publication the Report will undergo final copyediting as well as any error correction as necessary, consistent with the IPCC Protocol for Addressing Possible Errors.’

[38]Emissions, and the resulting greenhouse gas concentrations, do not diverge significantly between the

RCP4.5 and RCP6 scenarios until after 2050.

[39] Available at http://niclewis.files.wordpress.com/2013/11/ar5_tcr_estimates2.pdf.

[40] For Gillett et al. (2023) this is on a model-by-model regression basis; on the aggregate estimate method used for the range given in Figure 5 its best TCR estimate is 0.1 °C higher.

[41] See post at Climate Audit http://climateaudit.org/2013/12/09/does-the-observational-evidence-in-ar5-support-itsthe-cmip5-models-tcr-ranges/.

[42] Although not a peer-reviewed result, it is worth noting that the well-respected climate scientist Isaac Held argues that TCR is unlikely to exceed 1.8°C, and puts forward a best estimate of 1.4°C. See http://www.gfdl.noaa.gov/blog/isaac-held/2012/04/30/27-estimating-tcr-from-recent-warming/.

[43] The global warming estimates are based on multiplying the TCR estimate of 1.35 °C by the change in total forcing on each scenario between 2012 and 2081–2100 per the RCP forcings dataset, and adding 0.15°C for unrealised warming attributable to existing forcing, that as at 2012 was heating the ocean, becoming realised by 2081–2100. These TCR-based projections are consistent with more sophisticated calculations using a two-box model. Using the mean temperature for the decade ending in 2012 instead of that for 2012 would make no difference.

[44] Comparing the two sets of projections of future warming (from 2012 to 2081–2100), and excluding the low RCP2.6 scenario (for which the GCM overestimation is even higher). The projections based on TCR allow for warming 'in the pipeline' boosting future temperature rises. Model warming estimates of 1.7 × to 2.0× observationally-based estimates correspond to observationally-based estimates being 40% to 50% below model estimates.

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