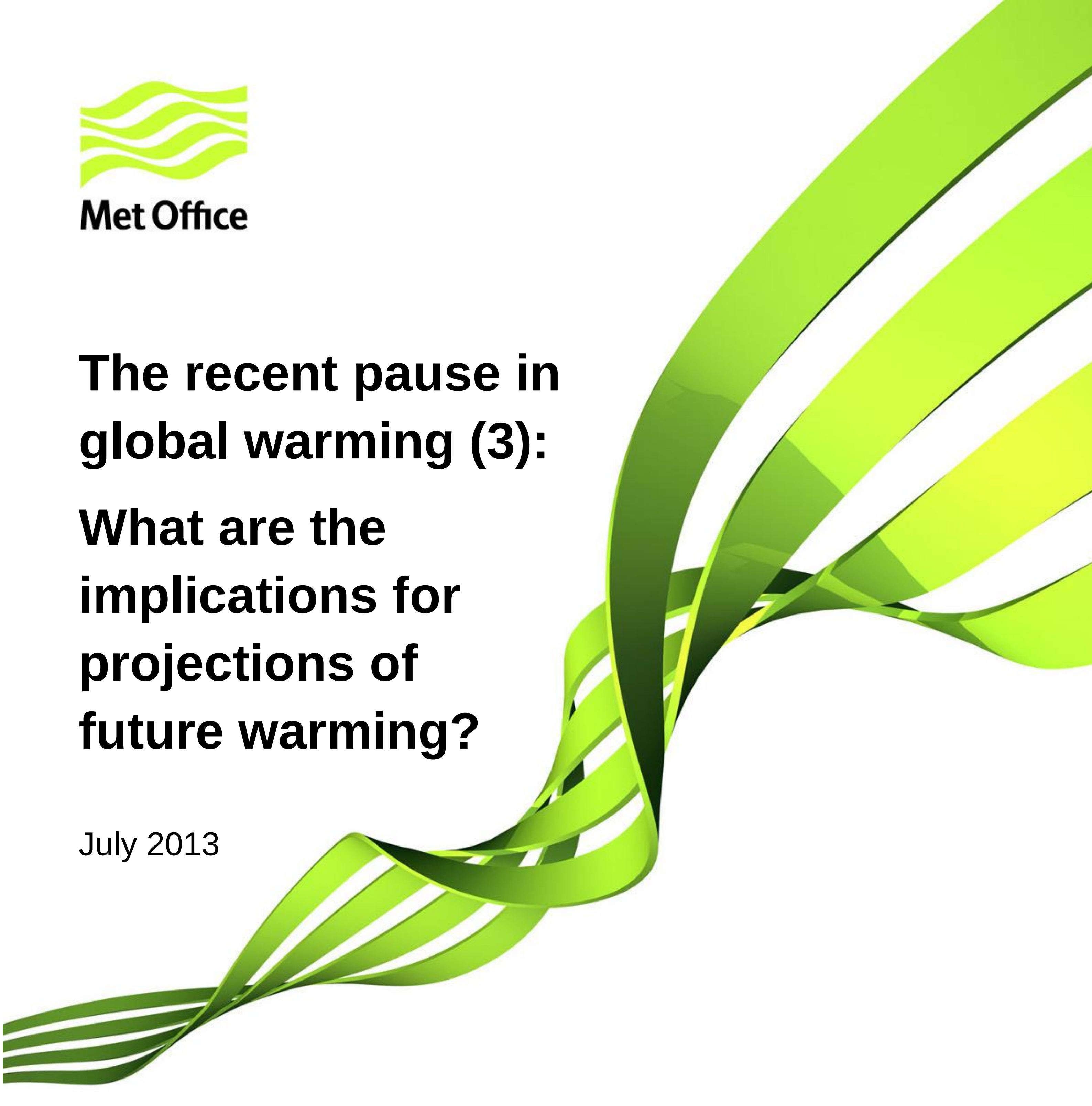

The recent pause in global warming (3):

What are the implications for projections of future warming?

July 2013

Contents

Executive summary

The recent pause in global surface temperature rise does not materially alter the risks of substantial warming of the Earth by the end of this century. Nor does it invalidate the fundamental physics of global warming, the scientific basis of climate models and their estimates of climate sensitivity.

Global mean surface temperatures rose rapidly from the 1970s, but there has been little further warming over the most recent 10 to 15 years to 2013. This has prompted speculation that human induced global warming is no longer happening, or at least will be much smaller than predicted. Others maintain that this is a temporary pause and that temperatures will again rise at rates seen previously.

This paper is the third in a series of three reports from the Met Office Hadley Centre that address the recent pause in global warming and seek to answer the following questions. What have been the recent trends in other indicators of climate over this period; what are the potential drivers of the current pause; and how does the recent pause affect our projections of future climate?

The purpose of this third report is to consider warming of the climate several decades into the future due to changes in atmospheric concentrations of greenhouse gases and aerosols. Two main questions are addressed:

- How have quantitative projections of future warming changed with the new generation of comprehensive climate models?
- Does the pause in global mean surface warming, observed in the last decade or so, alter projections of future warming?

Future warming depends on the *emissions* of greenhouse gases and on the *sensitivity* of the climate system to increased greenhouse gases (the amount of warming for given greenhouse gas concentrations).

The thrust of this paper is to address the question of climate sensitivity by considering two basic metrics of sensitivity of the climate system: the transient climate response (TCR) and the equilibrium climate sensitivity (ECS). Both were originally defined to compare the response of climate models to a specific scenario of increased concentrations of carbon dioxide. Their definition has now been extended to include observational estimates.

ECS is a measure of the long-term *equilibrium* response of the global surface temperature to stabilisation at a doubling of carbon dioxide concentrations. TCR describes the change in global surface temperature when carbon dioxide *reaches* a doubled concentration following a 1% rise in concentrations each year. It is generally lower than the equilibrium climate sensitivity because components such as the ocean, with its large thermal capacity, take a long time to adjust to a change in carbon dioxide concentrations.

The TCR is relevant to warming over the coming decades as greenhouse gas concentrations continue to rise. ECS is relevant to the eventual stabilisation of future warming if greenhouse gas concentrations stabilise.

The main conclusions of this report are:

- The new generation of comprehensive climate models produce similar ranges for TCR and ECS compared with the previous generation, although they simulate global patterns of climate and climate change with greater fidelity.
- Despite the recent pause in the global mean surface temperature rise, the upper ranges of TCR and ECS derived from extended observational records, and specifically including this period, are broadly consistent with the upper range from the latest generation of comprehensive climate models.
- When projections made by earlier climate models are verified against the subsequent observational record, it is shown that the projections cover the temperatures observed in the most recent decade, thus providing support for the overall validity of climate models and the fundamental physics of global warming.
- When projections from the newer climate models are combined with observations, including those from the last 10 years, the uncertainty range for warming out to 2050 is reduced. The very highest values of projected warming are eliminated, but the lower bound is largely unchanged. The *most likely warming* is reduced by only 10%, indicating that the warming that we might previously have expected by 2050 would be delayed by only a few years.

In conclusion, as demonstrated in this report, the science of climate change is continually moving forward as understanding increases, models improve, and the observational record becomes more extensive. This is allowing the climate science community to provide more robust evidence on which to base policy decisions. The recent pause in global surface temperature rise does not invalidate previous estimates of climate sensitivity. Nor does it materially alter the risks of substantial warming of the Earth by the end of this century.

1. Introduction

There has been an increase in the global mean near-surface temperature of around 0.8°C since the global instrumental record began in the mid-19th century and the most recent 10-year period remains the warmest on record. However global surface temperature increases have been much smaller over the most recent 15 years up to 2013. This has prompted speculation that human induced global warming is no longer happening, or at least will be much smaller than previously thought. As we note in the first report in this series, other elements of the climate system continue to show a warming world, whilst the second report suggests that the recent pause in surface warming may, in part, be due to internal variability in the oceans and how heat is taken up below the ocean surface.

The purpose of this third report is to consider projections of longer-term future warming due to emissions of greenhouse gases and aerosols in the light of recent trends in global mean temperature. The global climate science community now has available a new set of model projections of future climate from the 5th coupled model intercomparison project (CMIP5), in addition to new observations.

The focus here is on warming measured by global mean near surface temperature, because this simple metric measures the amount of past and future climate change due to human emissions of greenhouse gases and therefore remains a quantity of policy interest. For example, the UNFCCC’s ultimate goal is formulated in terms of limiting increases in this metric to no more than 2°C above pre-industrial levels.

The amount of future warming depends on two factors. The first involves future greenhouse gas and aerosol concentrations in the atmosphere, which depend on *future emission pathways*. It is important to emphasise, nevertheless, that there is a commitment to a certain degree of warming in the next 30 years or so due to the additional carbon that has already accumulated in the atmosphere. This is because a large fraction of emitted carbon remains in the atmosphere for more than a century. Even during the recent pause in global surface temperature rise, carbon dioxide concentrations have continued their inexorable rise from around 280ppmv in preindustrial times, passing 400ppmv for the first time in 2013.

The second determining factor is the *sensitivity* of the climate system to changes in concentrations of greenhouse gases, which essentially describes the amount of warming, via increased energy input to the Earth system (*radiative forcing)*, for given greenhouse gas concentrations. In the past fully comprehensive models of the climate system have generally been used to calculate climate sensitivity, but as global warming proceeds and the observational record extends, climate sensitivity can be estimated from observations, often in combination with the models.

It is worth emphasising that climate sensitivity emerges from the vast array of complex physical interactions and feedbacks acting over a wide range of time and space scales in the climate system. Climate sensitivity cannot be imposed in comprehensive climate models, nor can these complex models be tuned to give a particular value of climate sensitivity. Although the direct radiative forcing of greenhouse gases is known and constrained, it is the feedbacks in the climate system that ultimately determines the climate sensitivity. Again these are emergent properties of the climate models and result from complex interactions between the dynamics (e.g. winds in the atmosphere, current in the oceans) and thermodynamics (e.g. radiation, evaporation, condensation) of the climate system. Specifically, where clouds form is as much an expression of the dynamics of the system as the thermodynamics (e.g. Bony et al., 2004).

There are varying degrees of confidence in the sign and size of the dominant feedbacks in the climate system, and the response of clouds remains the dominant uncertainty. It is these uncertainties that lead to the range of climate sensitivities across the world's climate models.

Climate science moves forward continuously and often at pace, and that is reflected in model improvements and in changes in estimates of quantities such as climate sensitivity. Climate models seek to represent our best understanding of how the climate system works, and continuously evolve as our knowledge of the climate system improves and as increases in supercomputing resource allow the complexity and resolution of the models to increase. The resulting improvements in model performance are documented in Andrews et al. (2012, 2012a).

This report focuses on the latest estimates of climate sensitivity from observations, models, and models in combination with observations, and specifically addresses the question of whether the recent pause in global mean surface warming affects these estimates of climate sensitivity, and hence future projections of global surface temperature rise.

2. Measures of climate sensitivity

There are two basic metrics of sensitivity of the climate system: the *transient climate response* (TCR) and the *equilibrium climate sensitivity* (ECS). They have specific definitions that relate to the use of an idealised scenario of increasing atmospheric carbon dioxide (CO_2) concentrations within climate models. This is important because the TCR and ESC, as strictly defined, relate only to the climate sensitivity associated with the physical response of the climate system to increasing atmospheric CO_2 and not necessarily to other forcing agents.

TCR is defined as the mean change in global mean surface temperature at the time of doubling of atmospheric carbon dioxide (CO_2) concentrations from pre-industrial levels, in a scenario of a cumulative 1% increase in CO_2 per year. Hence TCR describes the change in global mean surface temperature in response to *reaching* a doubling of CO_2. ECS describes the *equilibrium* response of the climate system, as defined by the global surface temperature reached eventually after stabilisation of atmospheric concentrations *at* a doubling of CO_2.

The ECS tends to be greater than the TCR because the planet's surface temperature continues to rise as the Earth seeks to come into equilibrium with the radiative forcing, even after greenhouse gas concentrations have stabilised. This delay is because of the slow response time of some elements of the climate system, such as the oceans with their large thermal capacity. Climate simulations show that it can take several centuries for the climate system to reach equilibrium, all other external forcings remaining constant (e.g. volcanoes, Sun).

Clearly TCR is of practical relevance to warming over the coming decades as greenhouse gas concentration continues to rise. ECS is most relevant to the eventual stabilisation of future warming if greenhouse gas concentrations stabilise; it is used by the UNFCCC in its policy negotiations.

3. Transient Climate Response (TCR)

The TCR can be estimated in a variety of ways. These include estimates from simulations made with climate models, estimates made from observations, and estimates made by combining climate model and observationally-derived values. Estimates from each method are assessed in the following sections. Each method has its own assumptions, and so it is not possible to say that one method is superior to the others.

3.1 Estimates of Transient Climate Response from comprehensive climate models

Climate research centres around the world develop models of the Earth's climate, and these models participate in coordinated intercomparisons every 5 years or so. The 5th Coupled Model Intercomparison Project, CMIP5, has recently been assembled. The ability of CMIP5 models to simulate observed large-scale patterns of surface temperature show improvements over those submitted to the previous effort, CMIP3, which underpinned the IPCC 4th Assessment Report (Knutti et al, 2013).

Model estimates of the TCR are derived from specific simulations of climate change, where CO_2 concentrations increase systematically by 1% per year up to a doubling of CO_2 concentrations, to give an almost linear increase in radiative forcing. The TCR is computed from the temperature change at the point of reaching the doubling of CO_2.

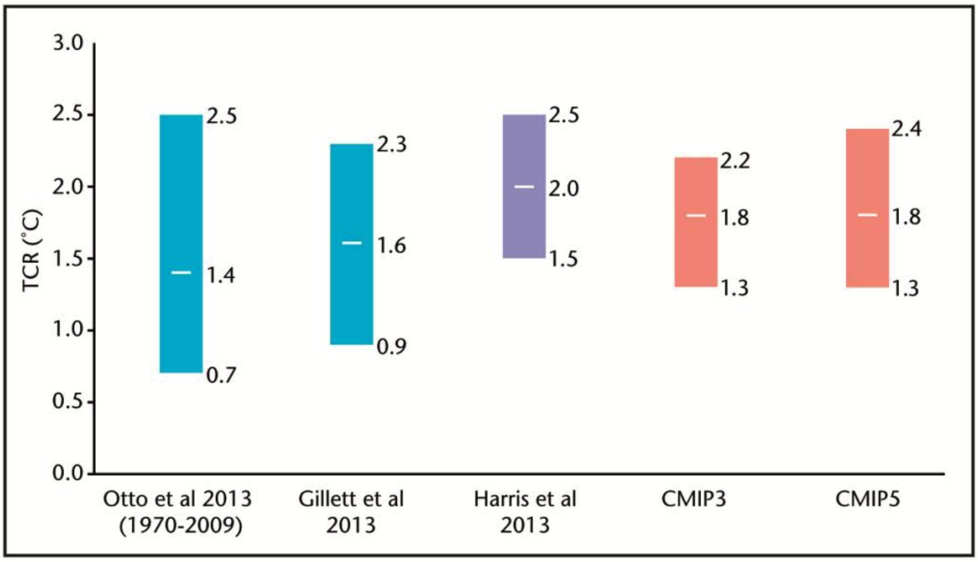

Figure 1: *Estimates of TCR from different sources. The bars show the range between 5th and 95th percentiles. White horizontal lines on each bar show the best estimate value for Otto et al (2013), mean value for Gillett et al (2013), median for Harris et al (2013), and multi-model mean for CMIP3 (IPCC 4th Assessment Report, Working Group 1) and CMIP5 (Forster et al, 2013). The colours denote source, with blue showing estimates based on observations, purple for model and observations, and orange for model only.*

The range of TCR estimates derived from the CMIP5 is 1.3°C to 2.4°C, which differs little from the CMIP3 estimates; the mean value is the same at 1.8°C. These results are presented graphically and compared with values from other methods of calculation in Figure

1[1]. The spread in TCR estimates across the models represents the uncertainties in the climate feedbacks and the ocean heat uptake. Cloud feedbacks have long been identified as the largest single source of this uncertainty (IPCC AR4, 2007) and this still appears to be the case in the CMIP5 models (Andrews et al., 2012, 2012a, Vial et al., 2013), despite many improvements in the representation of clouds (Jiang et al., 2012; Klein et al., 2013).

3.2 Estimates of Transient Climate Response from observations

An observational estimate of TCR can be obtained using the ratio of observed warming to the actual radiative forcing experienced by the planet. Here the actual radiative forcing comes from anthropogenic (CO_2 and aerosols) and natural sources (e.g. volcanoes), as well as changes in solar output, so it is not exactly equivalent to the TCR from models. When TCR is estimated using comprehensive climate models as described in Section 3.1, the radiative forcing is known because changes in atmospheric composition are imposed, and solar forcing is kept constant. This has the advantage of being able to isolate the climate system response to increasing atmospheric CO_2 concentrations which is not the case for observations.

A recent comprehensive study, based on making a simple calculation of the global energy budget based on observational estimates of surface temperature rise and radiative forcing, estimated that the TCR ranged from 0.7 to 2.5°C using data over the period 1970-2009 (Otto et al, 2013, see Figure 1). The uncertainty range derives from uncertainties in the global surface temperature estimated from observations and uncertainties in the estimated radiative forcing.

Observational period	**5th percentile of TCR**	**Most likely TCR**	**95th percentile of TCR**
1970s	0.3	1.0	3.0
1980s	0.7	1.4	2.9
1990s	0.9	1.6	3.1
2000s	0.9	1.4	2.0
1970-2009	**0.7**	**1.4**	**2.5**

Table 1: *Range of estimates of TCR (^{0}C) for different near present day observational periods from Otto et al. (2013).*

These authors also estimated the dependence of their values of TCR on the period of assessment, using observations from each decade since 1970 (see Table 1, with values taken from Otto et al, 2013). The upper estimate of the TCR is lower when using observations from the 2000s, and conversely higher when using the observations from the 1990s – a period of more rapid warming (see Figure 1 in the second report).

The lower value for the 2000s is associated with the recent pause in global surface temperature rise combined with continued rise in CO_2 concentrations. The lower bound of the

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[1] Note that the ranges shown in this report from the CMIP3 and CMIP5 models cover only the 5th to 95th percentile and the complete range will be larger.

TCR is around 0.7 - 0.9 for the most recent decades, whereas the uncertainty around the upper bound is much larger. Both exceed the bounds estimated from the models.

Part of the dependency of TCR on the observational period may well represent real decade-to-decade fluctuations in the strength of some climate feedbacks, such as rates of ocean heat uptake as discussed in the second report in this series. It raises the question of whether 10 years is sufficiently long to estimate the TCR without introducing substantial sampling errors. Otto et al (2013) state that, whilst the most recent decade may be better observed, "*caution is required in interpreting any short period, especially a recent one for which details of forcing and energy storage inventories are still relatively unsettled*".

Despite the fact that the first decade of the 21st century was a period during which there was a pause in the global mean surface temperature rise, the upper range of the 40-year average TCR derived from observations, including this pause period, is broadly consistent with the latest model results (Figure 1). As was also shown in the second report, averages of at least 30 years in length are needed to detect global warming above internal variability.

If, as the results presented in the first and second reports suggest, the recent pause in global mean surface temperature rise is not representative of other aspects of the climate system, which still show warming, and that some of the warming may be hidden below the ocean surface, then the TCR estimated from the most recent decade may not be a useful estimate of the TCR for projections of longer-term future warming.

3.3 Estimates of Transient Climate Response from studies combining comprehensive climate models and observations

Information from comprehensive climate models can be combined with observations to infer the likely range of the TCR. In this approach the magnitude and pattern of warming predicted by comprehensive climate models due to increasing CO_2 concentrations during the 20th century are compared with the magnitude and pattern of observed warming. The estimate of the TCR from the comprehensive climate models is then moderated based on this comparison.

This method combines the benefits of observations and models, although it is again subject to uncertainties in quantifying the radiative forcing from observations, as noted above. It is also susceptible to the potential for climate models to have compensating biases in the way in which they respond to different components of the radiative forcing (e.g. aerosols versus greenhouse gases). For example, if a climate model has an unrealistically large cooling from tropospheric aerosols, it may warm about the same as observed even though to do that it must have an unrealistically high TCR to increasing CO_2. Methods have now been devised to disentangle these compensating biases and to give more robust estimates of the TCR that are better constrained by observations.

Earlier studies applied to 20th century data show a range of estimates for the TCR of between approximately 1°C and 3°C that are consistent with observations (Stott and Forest, 2007). More recent studies, which include the observations from the past decade when the trend in global mean surface temperature has been low, give a range of between approximately 1°C and 2.5°C (Figure 1; Stott and Jones, 2012; Gillett et al, 2013).

An alternative approach has been developed recently by Harris et al (2013) drawing on a very large ensemble of projections with HadCM3 in which uncertainty in the response of the climate system to CO_2 forcing is comprehensively sampled by perturbing atmospheric, oceanic and land surface parameters. The projections are weighted by the likelihood that they reproduce both the observed mean climate in a number of climate variables, and the observed historical change in surface temperature up to 2000.

When applied to the estimation of the TCR, the method gives a 90% confidence range of 1.5°C to 2.5°C, with a median value of 2.0°C (Figure 1). The range is similar to that estimated from the CMIP3 and CMIP5 models. In this method the observational constraint does not play as great a role as it does in the estimates of Gillett et al (2013).

3.4 Summary of TCR estimates and the impact on warming to 2100

We have discussed several approaches to estimating the TCR, and the results are compared in Figure 1. There is good agreement between the upper estimates from each of the methods, but there is more spread in the lower estimates. The lower bounds from the observationally based estimates are less than the model studies suggest. It is worth emphasising again that the methods of estimating TCR are not the same between the models and observations, and different sources of uncertainty come into play. To reach the very low values quoted in Otto et al. (2013) would require negative feedbacks to be acting quite strongly to counteract the well understood physics of greenhouse gas radiative forcing, water vapour feedback and surface albedo feedback (e.g. Bony et al. 2006).

Whilst the TCR provides a useful metric of the sensitivity of the climate system to radiative forcing, it is the actual warming due to future scenarios of greenhouse gases and aerosols that is of more interest to many policy makers. Estimates can be made either using comprehensive climate models (e.g. Knutti et al, 2013), or derived from the approaches that combine observations and models, or derived for a given radiative forcing increase using an approximate scaling relationship[2]. This latter simple method is used here.

Figure 2 shows the estimated warming at 2100 associated with the TCR estimates given in Figure 1 and using the RCP8.5 emissions scenario[3], chosen because recent emissions have followed this pathway. Again there is greater agreement in the top of the range than in the bottom. The estimates of warming in Figure 2 illustrate the variation associated with the range of TCR estimates from different approaches. In reality, we know that other Earth system feedbacks, associated for example with the cycling of carbon through natural systems, will change the total radiative forcing and the range of expected warming (see e.g. Knutti et al 2013). A full discussion of these ranges is beyond the scope of this report and will be covered comprehensively in the IPCC 5th Assessment Report to be published in September 2013.

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[2] Temperature rise to 2100 is calculated as the product of the forcing to 2100 and the value of TCR, divided by the estimated forcing for a doubling of atmospheric CO2 concentrations. The approach should not be applied to stabilisation scenarios.

[3] RCP 8.5 – Representative Concentration Pathway; a scenario for the climate that provides a value of $8.5 Wm^{-2}$ radiative forcing in 2100. It is the highest of the four RCP pathways.

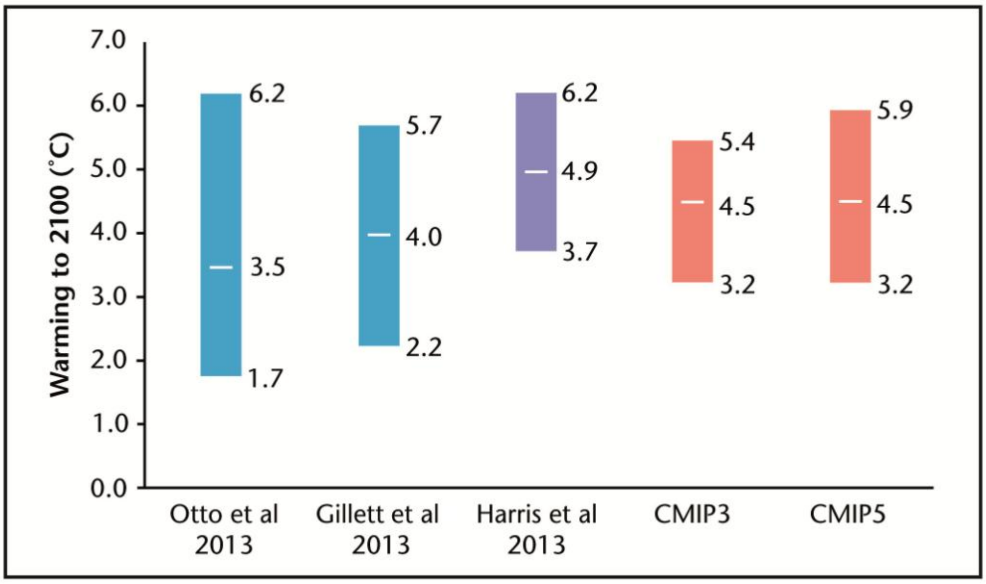

Figure 2: *Estimated warming at 2100, relative to pre-industrial levels under the RCP8.5 scenario. Values are calculated directly from the TCR estimates assuming that the temperature at 2100 is given by the product of the TCR and the radiative forcing at 2100, divided by the estimated radiative forcing associated with a doubling of atmospheric* CO_2*. This relationship is approximate. The ranges again show the 5th and 95th percentile with the median (most likely) value shown by the horizontal bar. The colours denote source, with blue showing estimates based on observations, purple showing model and observations, and orange for model only*

When the observations and climate models are combined using the method described in Gillett et al. (2013), the expected range of warming is slightly lower than expected from the CMIP5 climate models alone. In particular, there is some evidence that past aerosol forcing is too high in some models, which contributes to a greater warming in the future, as aerosols are removed from the atmosphere. This problem can be addressed by assessing whether model projections are consistent with temperature changes observed in the past century. This can be achieved by quantifying the extent to which increases in well-mixed greenhouse gases like CO_2 and changes in other anthropogenic and natural forcings have controlled observed temperature patterns around the globe.

In a new study Stott et al. (2013) combined multiple climate models into a single estimate of future warming rates consistent with past temperature changes, *including temperature changes over the first decade of the 21st century*. The method assumes that the temperature response is linearly related to the radiative forcing.

As Figure 3 demonstrates, when observational constraints, specifically past warming, are applied to climate model projections, then the high rates of warming simulated by some climate models seem now to be less likely. Also Stott et al. (2013) find that the most likely (median) warming under RCP scenarios is about 10% lower than the median warming projected by the CMIP5 models. To put this result into context, under a forcing scenario such as RCP8.5 shown in Figure 3, a 10% reduction in the TCR, from an estimate of 2°C, say, would imply that the warming previously expected by 2050 would be delayed by only a few years. In other words the recent pause in global surface temperature rise does not materially alter the risks of dangerous climate change. This study demonstrates the value of using observational constraints, in this case surface temperature, and notes the value of extending this further to include other key variables, such as ocean heat content.

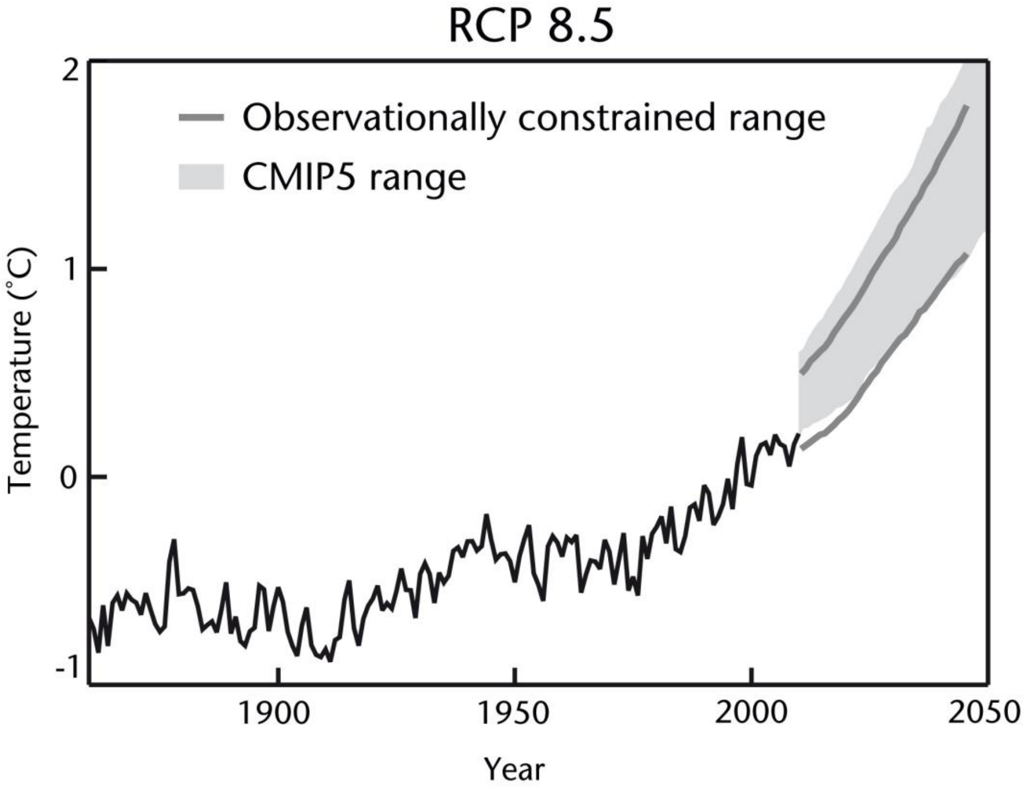

Figure 3: *Global mean temperature change as observed from the HadCRUT4 dataset (black line to 2010), and the 5th and 95th percentiles of the observationally constrained model projections from 2010 (grey lines). The grey shaded area shows 5th–95th percentiles of the full range of the CMIP5 model simulations. Projections follow the RCP8.5 scenario. Models are calibrated against the observed change from 1900 to present, and assumes that the temperature response to radiative forcing is linear. This limits the validity of the method for longer timescales, and hence results here are not presented beyond 2050. Figure from Stott et al. (2013).*

Finally, we investigate whether the recent observations of a pause in global surface warming invalidate past projections of climate change that have been made by climate research centres around the world on a continuous basis since the IPCC First Assessment Report published in 1990. We now have a sufficiently long record of model projections of climate change to do an independent verification of their performance against what has actually happened (e.g. Rahmstorf et al. 2007).

In a recent study, Allen et al. (2013) used projections of warming produced before 1996 and therefore based on information from much earlier models, to examine whether the most recent decade of observations invalidates the projections. Figure 4 shows the modelled 5th to 95th percentile plume of projections (grey area). The yellow diamonds show the 1-year global averaged temperature from recent observations, and the red diamonds show the 10-year global averaged temperatures from recent observations: they all lie within the projected plume. Thus, for the emissions scenario considered, the recent temperature record does not provide strong evidence to distrust projected warming ranges from older generations of climate models combined with earlier observations.

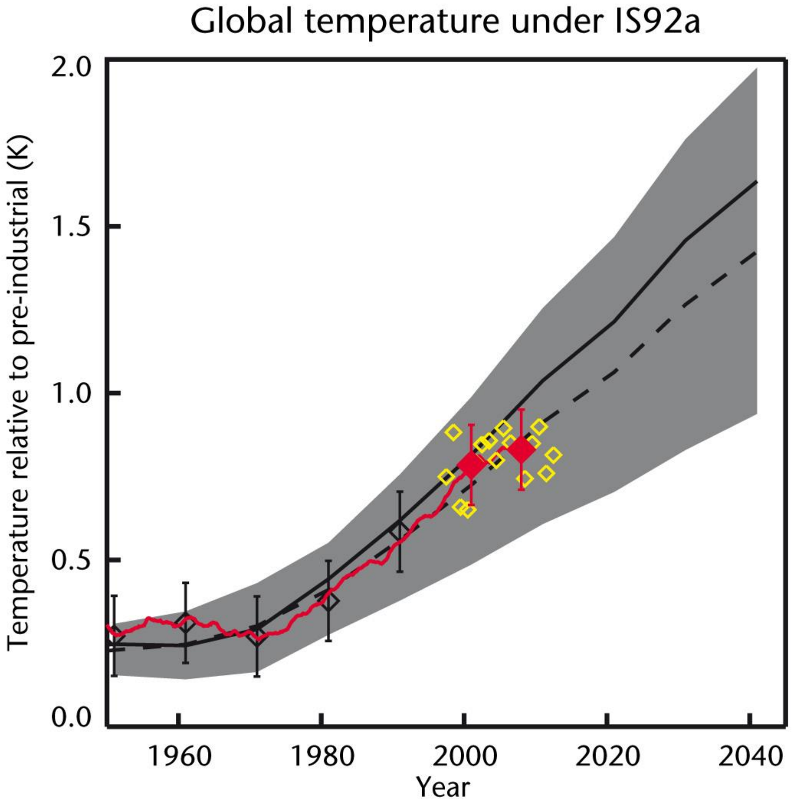

Figure 4. *Evaluation of past projections, made before 1996,of global mean temperature rise (relative to the pre-industrial era) under a version of the IS92a scenario*[4]*. The solid line shows the original mean estimated projection from the models. The dashed line shows the best estimate projection after combining the modelled projection with observations for the period 1946–1996 that were available at the time the projections were made.*

The grey shaded region indicates the 5–95% uncertainty interval in the projections. Large diamonds are 10-year means of the observed temperature: open black diamonds were used in the combination; solid red diamonds are the 10-year means of the recent observed temperature, which were not used in the combination with the models. Small yellow diamonds represent 1-year averages of the recent observations. Vertical bars on the black and red diamonds show 5–95% ranges on 10-year averaged temperatures expected from internal variability.

4. Equilibrium climate sensitivity (ECS) and stabilisation of climate change

Like the TCR, the ECS is determined by the feedbacks in the climate system (e.g. from changes in water vapour, atmospheric lapse-rate, sea-ice and clouds). In the absence of climate system feedbacks, a doubling of CO_2 would result in globally averaged surface warming of around 1°C. Positive feedbacks in the physical climate system, the largest of which is the water-vapour feedback, increase this number to over 2°C, as has been established for many years (e.g. Manabe and Wetherald, 1975). The estimates of the time

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[4] IS92a - The IS92 scenarios are defined in the IPCC Second Assessment Report. They include emissions of both greenhouse gases and aerosol precursors.

taken for the Earth's surface temperature to reach equilibrium following stabilisation of radiative forcing vary, but typically exceed a century.

ECS can be estimated from a range of methods: directly from observations, from comprehensive climate models or by combining models with observations. ECS can also be estimated using palaeoclimate reconstructions of periods in the distant past, such as the last glacial maximum. Again there are questions of accuracy and the comprehensiveness of palaeoclimate records.

Each approach has its own limitations. As for TCR, the observationally constrained results are sensitive to the specification of radiative forcing, which need to be modelled. The ECS also requires knowledge of the heat storage in the Earth system, particularly the oceans (see Figure 7 in the second report). As discussed at length in the second report, our knowledge of the ocean heat content and the processes through which the oceans take up heat is very limited. So, estimating the gain in energy by the current Earth system is very uncertain. This means that observational estimates of the ECS are prone to even greater uncertainty than for the TCR.

The uncertainty in the estimates of ECS from comprehensive climate models stems largely from the incomplete understanding and representation of cloud and other processes. The accuracy of palaeoclimate reconstructions is limited by the uncertainty in the reconstructed temperature, our understanding of the causes of the changes from present climate, and the degree of relevance of past climate change to a warming driven by increases in greenhouse gases.

Figure 5 shows a comparison of the ECS estimated from a range of methods. The most recent CMIP5 models have an estimated ECS range of approximately 2.1°C to 4.6°C (Forster et al, 2013), similar to the previous CMIP3 generation of models.

Observationally based approaches span a wider range than these model estimates, reflecting the difficulties in estimating radiative forcing and the change in energy content of the Earth system. The recent study by Otto et al (2013) used observations within a simple energy balance calculation, and found a 5th to 95th percentile range of ECS of 0.9°C to 5.0°C based on observations of global mean temperature from 1970-2009. The values reduced to 1.2°C to 3.9°C when based only on observations of the most recent decade. As for TCR the observations of most recent decade are not representative of the full observational record and so not expected to be representative of the longer term future.

Furthermore the lower bound of ECS values reported by Otto et al. (2013) seems at odds with the fundamental physics of climate sensitivity, involving black body radiation and water vapour feedbacks. These alone give a climate sensitivity of at least 2.0°C without considering the further, positive, surface albedo feedback related to snow and ice melt. To reach a climate sensitivity of less than 1.0°C would require extreme negative feedbacks to be invoked. A possible candidate is clouds, but recent estimates of the contribution from clouds to uncertainties in climate sensitivity (Vial et al. 2013) suggest that such an extreme negative feedback is unlikely.

The estimates from palaeoclimates[5] assume that the ECS associated with past changes is the same as that associated with doubling atmospheric carbon dioxide (see Crucifix, 2006). Most palaeo estimates of climate sensitivity are based on the last glacial maximum and use palaeo data or model simulations constrained by the palaeo data. The results cover a range of around 1.2°C to 5.2°C, with most studies giving a median between 2.3°C and 2.5°C (e.g. Schneider von Deimling et al, 2006; Schmittner et al, 2011 and Hargreaves et al, 2012).

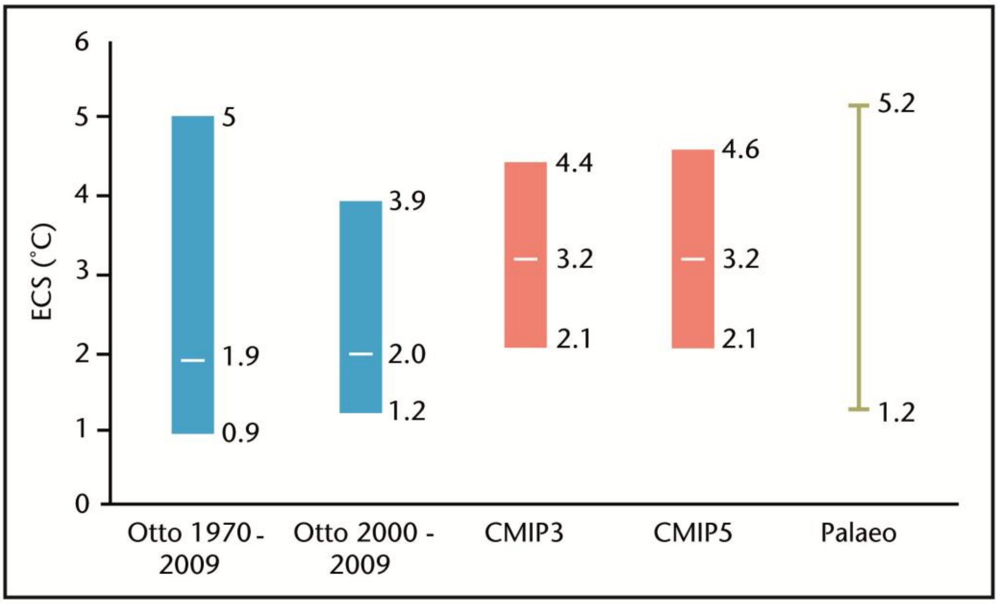

Figure 5: *Estimated ranges of ECS from different approaches. The bars show the range between 5th and 95th percentiles. White horizontal lines on each bar show most likely value for Otto et al (2013) and multi-model mean for CMIP3 (as used in IPCC 4th Assessment Report, Working Group 1) and CMIP5 (Forster et al, 2013). The colours denote source, with blue showing estimates based on observations, and orange for model only. The final khaki bar shows the range from palaeoclimate estimates[5].*

Finally, much of the interest in ECS relates to the amount of warming that would result if the radiative forcing were stabilised. In reality, other Earth system feedbacks, associated for example with the cycling of carbon through natural systems and releases of carbon from permafrost melt, will change, and are likely to increase the actual expected warming (see e.g. Knutti et al 2013). What is evident is that, even for the more conservative estimates derived from observations, the prospects of substantial global warming by the end of the century are not materially altered by the recent pause in global surface warming.

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[5] Because the range shown for the palaeoclimate estimates in Figure 5 is based on a variety of methods the range is not a strict 5% to 95% confidence estimate, hence the different marker used for these values.

Concluding remarks

This paper has considered recent developments in quantifying the long term warming of the climate to increases in greenhouse gas concentration in the light of the recent pause in global surface temperature rise, and whether this has radically altered estimates of climate sensitivity and therefore future projections of global surface temperature rise.

Despite the fact that the first decade of the 21st century has been a period during which there was very little global mean surface temperature rise, the range of TCR estimates from the CMIP5 models lies within the TCR derived from observations, including this period. Indeed it can be shown that even the projections from much earlier models encompass the subsequent surface temperature observations, including the most recent decade. Therefore the physical basis of climate models and the projections they produce have not been invalidated by the recent pause in global surface temperature rise.

When projections from the newer CMIP5 models are combined with observations, and specifically including the surface temperatures from the last 10 years, the upper bound of projections of warming are slightly reduced, but the lower bound is largely unchanged. More importantly, the *most likely warming* is reduced by only 10%, indicating that the warming that we might previously have expected by 2050 would be delayed by only a few years.

Observational constraints on the ECS are more problematic because of uncertainties in energy storage in the Earth system. Again the models continue to provide a consistent range of values for the ECS, lying within the uncertainty range of the observationally-based estimates.

In conclusion, the recent pause in global surface temperature rise does not invalidate climate models or their estimates of climate sensitivity. It does however raise some important questions about how well we understand and observe the energy budget of the climate system, particularly the important role of the oceans in taking up and redistributing heat, as highlighted in the second report. In particular, this report emphasises that the recent pause in global surface warming does not, in itself, materially alter the risks of substantial warming of the Earth by the end of this century.

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Professor Julia Slingo OBE, Met Office Chief Scientist
Professor Stephen Belcher, Head of the Met Office Hadley Centre
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