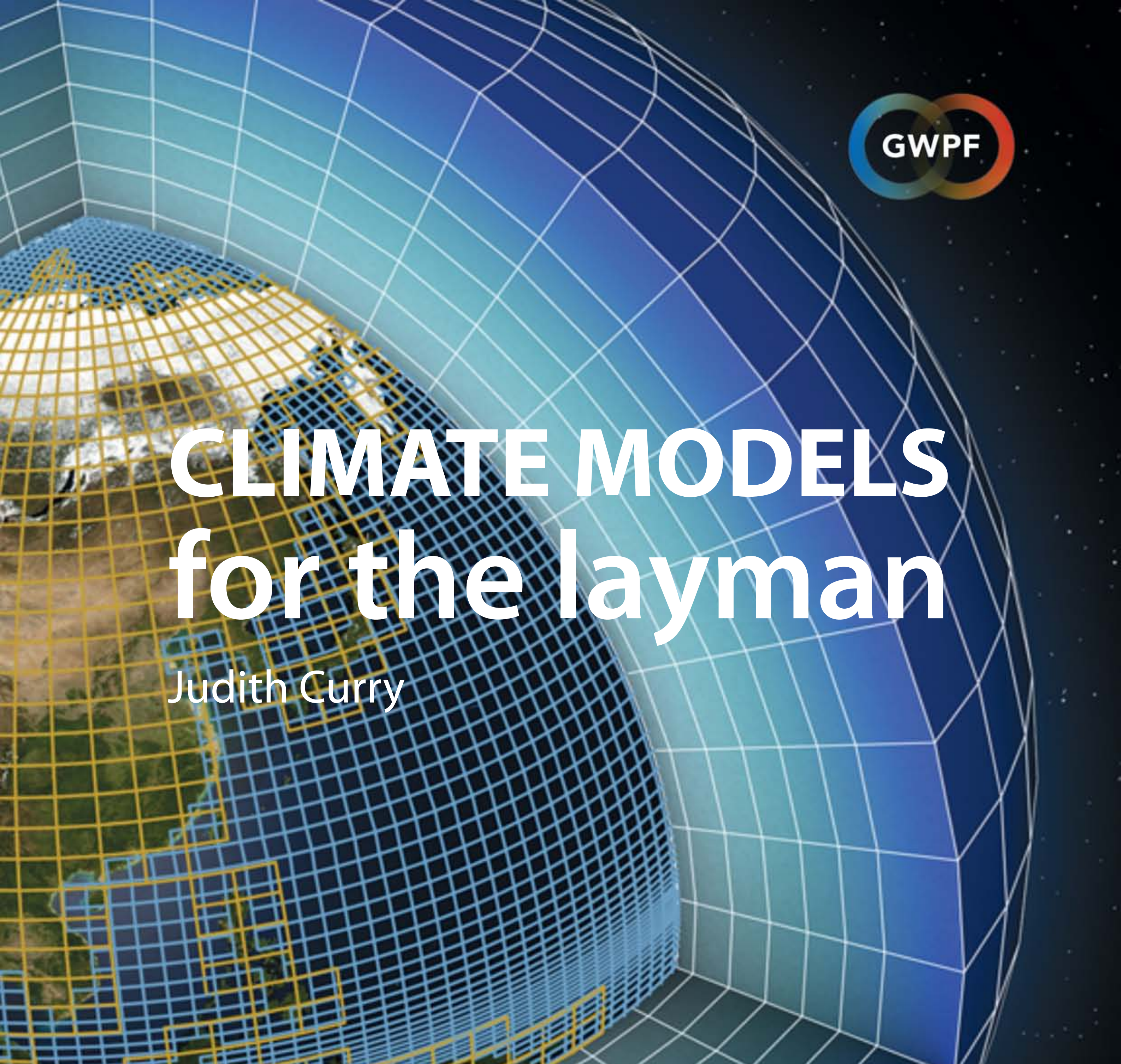

CLIMATE MODELS for the layman

Judith Curry

The Global Warming Policy Foundation

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About the author

Professor Judith A. Curry is the author of over 180 scientific papers on weather and climate and is a recipient of the Henry G. Houghton Research Award from the American Meteorological Society in 1992. She recently retired from the Georgia Institute of Technology, where she held the positions of Professor and Chair of the School of Earth and Atmospheric Sciences. She is currently President of Climate Forecast Applications Network.

Executive Summary

There is considerable debate over the fidelity and utility of global climate models (GCMs). This debate occurs within the community of climate scientists, who disagree about the amount of weight to give to climate models relative to observational analyses. GCM outputs are also used by economists, regulatory agencies and policy makers, so GCMs have received considerable scrutiny from a broader community of scientists, engineers, software experts, and philosophers of science. This report attempts to describe the debate surrounding GCMs to an educated but nontechnical audience.

Key summary points

- GCMs have not been subject to the rigorous verification and validation that is the norm for engineering and regulatory science.
- There are valid concerns about a fundamental lack of predictability in the complex nonlinear climate system.
- There are numerous arguments supporting the conclusion that climate models are not fit for the purpose of identifying with high confidence the proportion of the 20th century warming that was human-caused as opposed to natural.
- There is growing evidence that climate models predict too much warming from increased atmospheric carbon dioxide.
- The climate model simulation results for the 21st century reported by the Intergovernmental Panel on Climate Change (IPCC) do not include key elements of climate variability, and hence are not useful as projections for how the 21st century climate will actually evolve.

Climate models are useful tools for conducting scientific research to understand the climate system. However, the above points support the conclusion that current GCMs are not fit for the purpose of attributing the causes of 20th century warming or for predicting global or regional climate change on timescales of decades to centuries, with any high level of confidence. By extension, GCMs are not fit for the purpose of justifying political policies to fundamentally alter world social, economic and energy systems. It is this application of climate model results that fuels the vociferousness of the debate surrounding climate models.

1 What is a global climate model?

Global climate models (GCMs) attempt to create a coarse-grained simulation of the Earth's climate system using computers. GCMs have modules that model the atmosphere, ocean, land surface, sea ice and glaciers. The atmospheric module simulates the evolution of the winds, temperature, humidity and atmospheric pressure using complex mathematical equations that can only be solved using computers. GCMs also include mathematical equations describing the oceanic circulation, how it transports heat, and how the ocean exchanges heat and moisture with the atmosphere. Climate models include a land surface submodel that describes how vegetation, soil, and snow or ice cover exchange energy and moisture with the atmosphere. GCMs also include submodels of sea ice and glacier ice. While some of the equations in climate models are based on the laws of physics such as Newton's laws of motion and the first law of thermodynamics, there are key processes in the model that are approximated and not based on physical laws.

To solve these equations on a computer, GCMs divide the atmosphere, oceans, and land into a three-dimensional grid system (see Figure 1). The equations are then calculated for each cell in the grid – repeatedly for each of the time steps that make up the simulation period.[1]

The number of cells in the grid system determines the model 'resolution' (or granularity), whereby each grid cell effectively has a uniform temperature, and so on. Common resolutions for GCMs are about 100–200 km in the horizontal direction, 1 km vertically, and a time-stepping resolution typically of 30 min. While at higher resolutions, GCMs represent processes somewhat more realistically, the computing time required to do the calculations increases substantially – a doubling of resolution requires about 10 times more computing power, which is currently infeasible at many climate modelling centers. The coarseness of the model resolution is driven by the available computer resources, with tradeoffs made between model resolution, model complexity, and the length and number of simulations to be conducted. Because of the relatively coarse spatial and temporal resolutions of the models, there are many important processes that occur on scales that are smaller than the model resolution (such as clouds and rainfall; see inset in Figure 1). These subgrid-scale processes are represented using 'parameterisations', which are simple formulas that attempt to approximate the actual processes, based on observations or derivations from more detailed process models. These parameterisations are 'calibrated' or 'tuned' to improve the comparison of the climate model outputs against historical observations.

The actual equations used in the GCM computer codes are only approximations of the physical processes that occur in the climate system. While some of these approximations are highly accurate, others are unavoidably crude. This is because the real processes they represent are either poorly understood or too complex to include in the model given the constraints of the computer system. Of the processes that are

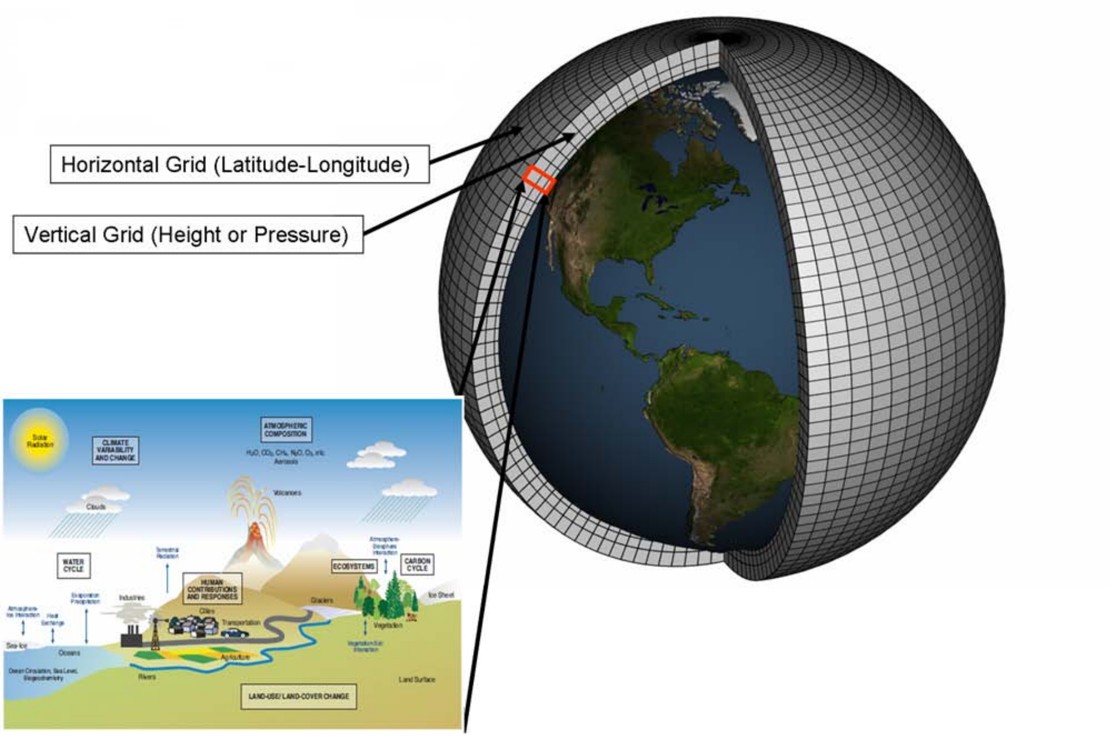

Figure 1: Schematic of a global climate model.

most important for climate change, parameterisations related to clouds and precipitation remain the most challenging, and are responsible for the biggest differences between the outputs of different GCMs.

GCMs are used for the following purposes:

- *Understanding how the climate system works:* sensitivity experiments are used to turn off, constrain or enhance certain physical processes or external forcings (for example, carbon dioxide, volcanoes, solar output) to see how the system responds.
- *Reproducing past climate states:* understanding the causes of past climate variability and change (for example, how much of the change can be attributed to human causes, such as carbon dioxide, versus natural causes such as solar variations, volcanic eruptions, and slow circulations in the ocean).
- *Global climate change:* simulation of future climate states, from decades to centuries, for example simulations of future climate states under different emissions scenarios.
- *Attributing extreme weather:* prediction and attribution of the statistics of extreme weather events (for example, heat waves, droughts, hurricanes).

- *Regional climate change:* projections of future regional climate variations to support decision-making-related adaptation to climate change.
- *Guidance for emissions reduction policies.*
- *Social cost of carbon:* the output from GCMs provides the raw data used to calculate the social cost of carbon.

The specific objectives of a GCM vary with purpose of the simulation. Generally, when simulating the past climate using a GCM, the objective is to correctly simulate the spatial variation of climate conditions in some average sense. When predicting future climate, the aim is not to simulate conditions in the climate system on any particular day, but to simulate conditions over a longer period – typically decades or more – in such a way that the statistics of the simulated climate will match the statistics of the actual future climate.

There are more than 20 international climate modelling groups that contribute climate model simulations to the IPCC assessment reports. Many of the individual climate modelling groups contribute simulations from several different models. Why are there so many different climate models? Is it possible to pick a 'best' climate model?

There are literally thousands of different choices made in the construction of a climate model (for example, resolution, complexity of the submodels, or the parameterisations). Each different set of choices produces a different model having different sensitivities. Further, different modelling groups have different focal interests, for example long paleoclimate simulations, details of ocean circulations, nuances of the interactions between aerosol particles and clouds, or the carbon cycle. These different interests focus their limited computational resources on a particular aspect of simulating the climate system, at the expense of others.

Is it possible to select a 'best' model? Well, several models generally show a poorer performance overall when compared with observations. However, the best model depends on how you define 'best', and no single model is the best at everything.

2 The reliability of GCMs

Because of the complexity of GCMs, the notion of a correct or incorrect model is not well defined. The relevant issue is how well the model reproduces reality and whether the model is fit for its intended purpose.

Statistician George Box famously stated: 'All models are wrong but some are useful'.[2] All models are imperfect; we don't need a perfect model, just one that serves its purpose. Aeroplanes are designed using models that are inadequate in their ability to simulate turbulent flow. Financial models based upon crude assumptions about human behaviour have been used for decades to manage risk. In the decision-making process, use of a model depends on a variety of factors, one of which is its credibility.

Climate model development has followed a pathway mostly driven by scientific curiosity and computational limitations. GCMs were originally designed as a tool to help understand how the climate system works. They are used by researchers to represent aspects of climate that are extremely difficult to observe, to experiment with theories in a new way by enabling hitherto infeasible calculations, to understand a complex system of equations that would otherwise be impenetrable, and to explore the climate system to identify unexpected outcomes. As such, GCMs are an important element of climate research.

Why do scientists have confidence in GCMs?

Scientists who develop climate models and use their results are convinced (at least to some degree) of their usefulness for their research. They are convinced because of the model's relation to the physical understanding of the processes involved, consistency of the simulated responses among different models and different model versions, and the ability of the model and model components to simulate historical observations.

Confidence in a forecast model depends critically on evaluation of the forecasts against real-world observations, both using historical data (hindcasts) and actual forecasts. Evaluation of forecasts is feasible for short time horizons (in other words, weather forecasts). Capturing the phenomena in hindcasts and previous forecasts is a necessary, but not sufficient, condition for the model to capture the phenomena in the future.

Why are some scientists concerned about the reliability of GCMs?

Uncertainties in GCMs arise from uncertainty in model structure, model parameters and parameterisations, and initial conditions. Calibration – ad hoc adjustments or 'tuning' – is necessary to address parameters that are unknown or inapplicable at the model resolution, and also in the linking of submodels. Continual ad hoc adjustments of a model can mask underlying deficiencies in the model's structural form.

Concerns about evaluating climate models have been raised in the context of model calibration/tuning practices. A remarkable article was recently published in *Science* entitled 'Climate scientists open up their black boxes to scrutiny'.[3]

> Indeed, whether climate scientists like to admit it or not, nearly every model has been calibrated precisely to the 20th century climate records – otherwise it would have ended up in the trash. 'It's fair to say all models have tuned it,' says Isaac Held, a scientist at the Geophysical Fluid Dynamics Laboratory, another prominent modelling center, in Princeton, New Jersey.

We are now in a situation whereby matching the 20th century historic temperatures is no longer a good metric for determining which models are good or bad. The implication is that models that match 20th century data as a result of model calibration/tuning using the same 20th century data are of dubious use for determining the causes of 20th century climate variability.

Agreement between model simulations and data does not imply that the model gets the correct answer for the right reasons. For example, all of the coupled climate models used in the IPCC Fourth Assessment Report (2007) reproduce the time series for the 20th century of globally averaged surface temperature anomalies, yet they produce markedly different simulations of the 21st century climate. Further, tuning climate models to observations during the period 1975–2000 tunes the model to warm phases of natural internal variability, resulting in oversensitivity of the models to carbon dioxide. Hence, success in reproducing past states provides only a limited kind of confidence in simulation of future states.

Summary

GCMs are important tools for understanding the climate system. However, there are broad concerns about their reliability:

- GCM predictions of the impact of increasing carbon dioxide on climate cannot be rigorously evaluated on timescales of the order of a century.
- There has been insufficient exploration of GCM uncertainties.
- There are an extremely large number of unconstrained choices in terms of selecting model parameters and parameterisations.
- There has been a lack of formal model verification and validation, which is the norm for engineering and regulatory science.
- GCMs are evaluated against the same observations used for model tuning.
- There are concerns about a fundamental lack of predictability in a complex nonlinear system.

3 The failings of climate models

As they have matured, GCMs are being increasingly used to provide information to policymakers. They are being used as the basis for international climate and energy policy, so it is important to assess their adequacy for this purpose. In particular, GCM fitness needs to be assessed for:

- understanding the causes of 20th century climate change

- simulation of climate states in the 21st century under different emissions scenarios.

The focus of this section is on two general topics where GCMs are inadequate:

- determination of climate sensitivity to increasing carbon dioxide
- the chaotic nature of the climate system and internal climate variability.

Climate sensitivity to carbon dioxide

Human-caused warming depends not only on how much carbon dioxide is added to the atmosphere, but also on how 'sensitive' the climate is to that carbon dioxide. Climate sensitivity is defined as the global surface warming that occurs when the concentration of carbon dioxide in the atmosphere doubles. If climate sensitivity is high, then we can expect substantial warming in the coming century as emissions continue to increase. If climate sensitivity is low, then future warming will be substantially lower.

The equilibrium climate sensitivity (ECS) is defined as the change in global mean surface temperature that is caused by a doubling of the atmospheric carbon dioxide concentration after the climate system has had several centuries to respond. It is not possible to measure ECS directly; it can be estimated from climate model simulations and from historical observations using a simple energy balance model.

The IPCC Fourth Assessment Report (2007) conclusion on climate sensitivity is stated as:

> The equilibrium climate sensitivity…is likely to be in the range 2°C to 4.5°C with a best estimate of about 3°C and is very unlikely to be less than 1.5°C. Values higher than 4.5°C cannot be excluded.

The IPCC Fifth Assessment Report (2013) conclusion on climate sensitivity is stated as:

> Equilibrium climate sensitivity is likely in the range 1.5°C to 4.5°C (high confidence), extremely unlikely less than 1°C (high confidence), and very unlikely greater than 6°C (medium confidence)

This likely range of ECS values varies by a factor of three. Whether or not human-caused global warming is dangerous or not depends critically on whether the ECS value is closer to 1.5°C or 4.5°C. Research over the past three decades has not narrowed this range – the 1979 National Academy of Sciences study (the so-called 'Charney Report') cited a likely range for ECS of between 1.5 and 4.5°C.

In fact, it seems that uncertainty about value of ECS has *increased* since the 2007 Fourth Assessment. The bottom of the 'likely' range has been lowered from 2 to 1.5°C in the 2013 Fifth Assessment Report, whereas the Fourth Assessment Report stated that ECS is very unlikely to be less than 1.5°C. It is also significant that the Fifth Assessment does not cite a best estimate, whereas the Fourth Assessment cites a best estimate of 3°C. The stated reason for not citing a best estimate in the Fifth Assessment is the substantial discrepancy between observation-based estimates of ECS (lower) and estimates from climate models (higher).

Table 1 compares the values of ECS determined by: the IPCC Fourth Assessment Report (2007),[4] the Fifth Assessment Report (2013),[5] the CMIP5 climate models cited in the Fifth Assessment Report,[6] the observational analysis of Lewis and Curry (2014)[7] and the update by Lewis (2016) with lower aerosol forcing.[8]

Table 1: Values of equilibrium climate sensitivity.

	Best estimate	**Percentile**	
		5th	**95th**
	(°C)	(°C)	(°C)
Fourth Assessment (2007)	3.0	1.5	–
Fifth Assessment (2013)	–	1.0	6.0*
CMIP5 models (2013)	3.22	2.1	4.7
Lewis and Curry (2014)	1.64	1.05	4.05
Lewis (2016)	1.54	1.12	2.38**

*90th percentile **updated through 2015.

Lewis and Curry (2014) used an observation-based energy balance approach to estimate ECS. Their calculations used the same values (including uncertainties) for changes in greenhouse gases and other drivers of climate change as given in the Fifth Assessment. However, their range of values for ECS were approximately half those determined from the CMIP5 climate models. In addition, the range of values was much narrower, with far lower upper limits, than reported by the IPCC.

Other recent papers also find comparably low values of ECS,[9,10] and the latest research suggests *even lower* values. The greatest uncertainty in ECS estimates is in accounting for the effects of small aerosol particles in the atmosphere (from pollution or natural sources), which have a cooling effect on the climate (partially counteracting the greenhouse warming). A recent paper by IPCC lead author Stevens[11] constrains the impact of aerosols on climate to be significantly smaller than assumed in the Fifth Assessment Report. Lewis has re-run the calculations used in Lewis and Curry (2014) using aerosol impact estimates in line with Stevens' paper.[12] Most significantly, the upper bound (95th percentile) is lowered to 2.38°C (Table 1).

Many of the climate model simulations used for the Fifth Assessment (CMIP5) use values of aerosol forcing that appear to be far too high. Climate model simulations that are re-assessed and recalibrated to account for smaller values of aerosol forcing can be used to clarify the upper bound of ECS. In a recent workshop presentation,[13] Stevens argued for an upper bound to ECS of 3.5°C based on analyses of climate models. Research continues to assess the methods used to estimate climate sensitivity. However, the reduced estimates of aerosol cooling lead inescapably to reductions in the estimated upper bound of climate sensitivity.

In GCMs, the equilibrium climate sensitivity is an 'emergent property' that is not directly calibrated or tuned. While there has been some narrowing of the range of modelled climate sensitivities over time, models still can be made to yield a wide range of sensitivities by altering model parameterisations. Model versions can be rejected or not, subject to the modellers' own preconceptions, expectations and biases about the outcome of ECS calculations.

What is the source of the discrepancies in ECS among different climate models, and between climate models and observations? In a paper entitled 'What are climate models missing?'[14] Stevens and Bony argue that:

> There is now ample evidence that an inadequate representation of clouds and moist convection, or more generally the coupling between atmospheric water and circulation, is the main limitation in current representations of the climate system.

What are the implications of these discrepancies for the value of ECS? If it is less than 2°C versus more than 4°C, then the conclusions regarding the causes of 20th century warming and the likely amount of 21st century warming are substantially different. Further, the discrepancy between observational and GCM estimates of climate sensitivity is substantial and of significant importance to policymakers. ECS and the level of uncertainty in its value are key inputs into the economic models that drive cost–benefit analyses and estimates of the social cost of carbon.

Chaos and natural internal climate variability

Variations in climate can be caused by external forcing, such as solar variations, volcanic eruptions or changes in atmospheric composition such as an increase in carbon dioxide. Climate can also change owing to internal processes within the climate system (internal variability). The best-known example of internal climate variability is El Niño/La Niña. Modes of decadal to centennial to millennial internal variability arise from the slow circulations in the oceans. As such, the ocean serves as a 'fly wheel' on the climate system, storing and releasing heat on long timescales and acting to stabilise the climate. As a result of the time lags and storage of heat in the ocean, the climate system is never in equilibrium.

With regards to multi-decadal internal variability, the IPCC reports consider this issue primarily in context of detection of a human-caused warming signal above the background 'noise' of natural variability. However, other interpretations of the climate system argue that the natural internal variability constitutes the instrinsic climate signal.

Many processes in the atmosphere and oceans are nonlinear, which means that there is no simple proportional relation between cause and effect. The nonlinear dynamics of the atmosphere and oceans are described by the Navier–Stokes equations[15] (based on Newton's laws of motion), which form the basis of prediction of winds and circulation in the atmosphere and oceans. The solution of Navier–Stokes equations is one of the most vexing problems in all of mathematics: the Clay Mathematics Institute[16] has declared this to be one of the top seven problems in all of mathematics and is offering a $1 million prize for its solution.

Arguably the most fundamental challenge with GCMs lies in the coupling of two chaotic fluids: the ocean and the atmosphere. Weather has been characterised as being in state of deterministic chaos,[17] owing to the sensitivity of weather forecast models to small perturbations in initial conditions of the atmosphere. The source of the chaos is nonlinearities in the Navier–Stokes equations. A consequence of sensitivity to initial conditions is that beyond a certain time the system will no longer be predictable; for weather this predictability timescale is a matter of weeks.

GCM simulations are also sensitive to initial conditions (even in an average sense). Coupling a nonlinear, chaotic atmospheric model to a nonlinear, chaotic ocean model gives rise to something much more complex than the deterministic chaos of a weather model, particularly under conditions of externally forced changes (such as is the case for increasing concentrations of carbon dioxide). Coupled atmosphere/ocean modes of internal variability arise on timescales of weeks, years, decades, centuries and millennia. These coupled modes give rise to instability and chaos. How to characterise them is virtually impossible using current theories of nonlinear dynamical systems, particularly in situations involving transient changes of parameter values. Stainforth et al.[18] refer to this situation as 'pandemonium'.

Fitness for purpose: attribution of 20th century warming

So, what does this mean for the fitness for purpose of climate models to determine the causes of the 20th century warming? The combination of uncertainty in the transient climate response (sensitivity) and the uncertainties in the magnitude and phasing of the major modes in natural internal variability preclude an unambiguous separation of externally forced climate variations from natural internal climate variability. If the climate sensitivity is at the low end of the range of estimates, and natural internal variability is on the strong side of the distribution of climate models, different conclusions are drawn about the relative importance of human causes to the 20th century warming.

Global surface temperature anomalies since 1850 are shown in Figure 2. Climate model simulations for the same period are shown in Figure 3. The modelled global surface temperature matches closely the observed temperatures for the period 1970–2000. However, the climate models do not capture the large warming from 1910 to

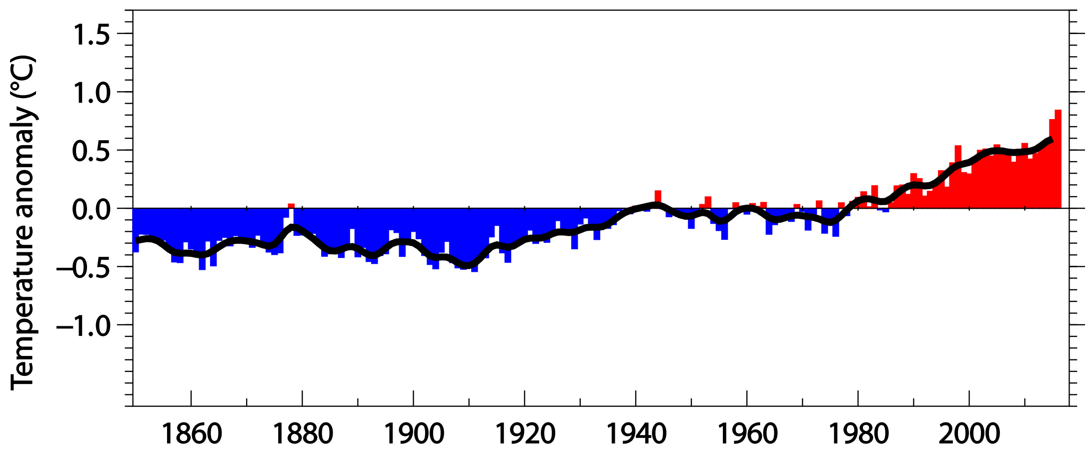

Figure 2: Global surface temperature anomalies from the UK HadCRUT4 dataset.[19]

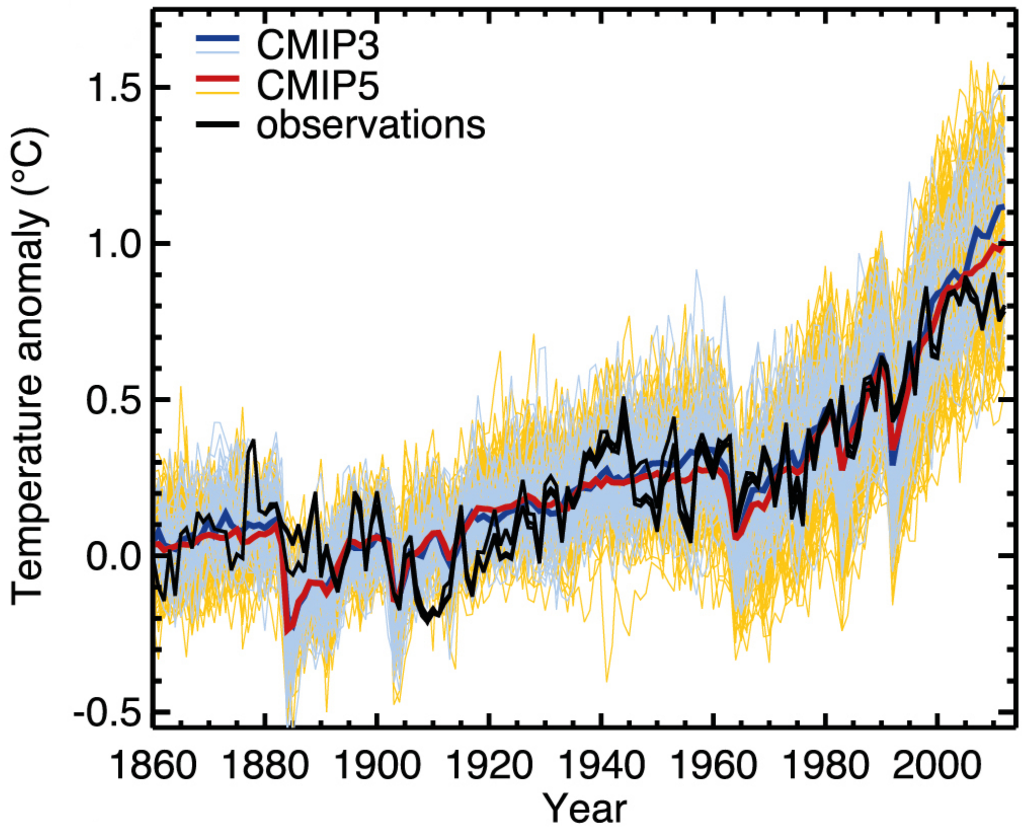

Figure 3: Comparison of the CMIP3 and CMIP5 simulations of global surface temperature anomolies with observations.

Source: Figure 10.1 from the IPCC AR5.

1940, the cooling from 1940 to the late 1970s and the flat temperatures in the early 21st century.

The key conclusion of the Fifth Assessment Report[20] is that it is extremely likely that more than half of the warming since 1950 has been caused by humans, and climate model simulations indicate that all of this warming has been caused by humans.

If the warming since 1950 was caused by humans, then what caused the warming during the period 1910–1940? The period 1910–1940 comprises about 40% of the warming since 1900, but is associated with only 10% of the carbon dioxide increase since 1900. Clearly, human emissions of greenhouse gases played little role in this early warming. The mid-century period of slight cooling from 1940 to 1975 – referred to as the 'grand hiatus' – has also not been satisfactorily explained.

Apart from these unexplained variations in 20th century temperatures, there is evidence that the global climate has been warming overall for the past 200 years, or even longer. While historical data becomes increasingly sparse in the 19th century, the Berkeley Earth Surface Temperature Project has assembled the available temperature data over land, back to 1750 (Figure 4). The Berkeley Earth analysis shows a warming trend back to 1800, with considerable variability around the turn of the 19th century. Some of this can be attributed to large volcanic eruptions; this was also the time of the Dalton solar activity minimum (1791–1825). Paleoclimate reconstructions of Northern Hemisphere climate – such as from tree rings and boreholes – indicate that overall warming may have occurred for the past 300–400 years.[22] Humans contributed little, if anything, to this early global warming.

What could be the cause of a 300–400 year period of secular warming? The obvious places to look are to the sun and the oceans. Ocean circulation patterns influence climate also on century-to-millennial timescales. Sun–climate connections are receiving renewed interest, as evidenced by the National Academies Workshop Report 'The Effects of Solar Variability on Earth's Climate'.[23] Understanding and explaining the climate variability over the past 400 years, prior to 1950, has received far too little attention. Without this understanding, we should place little confidence in the IPCC's explanations of warming since 1950.

Summary

Anthropogenic (human-caused) climate change is a theory in which the basic mechanism is well understood, but of which the potential magnitude is highly uncertain. What does the preceding analysis imply for the IPCC's 'extremely likely' attribution of anthropogenically caused warming since 1950? Climate models imply that all of the warming since 1950 can be attributed to humans. However, there have been large variations in global/hemispheric climate on timescales of 30 years, which are the same duration as the late 20th century warming. The IPCC does not have convincing explanations for previous 30-year periods in the 20th century, notably the warm-

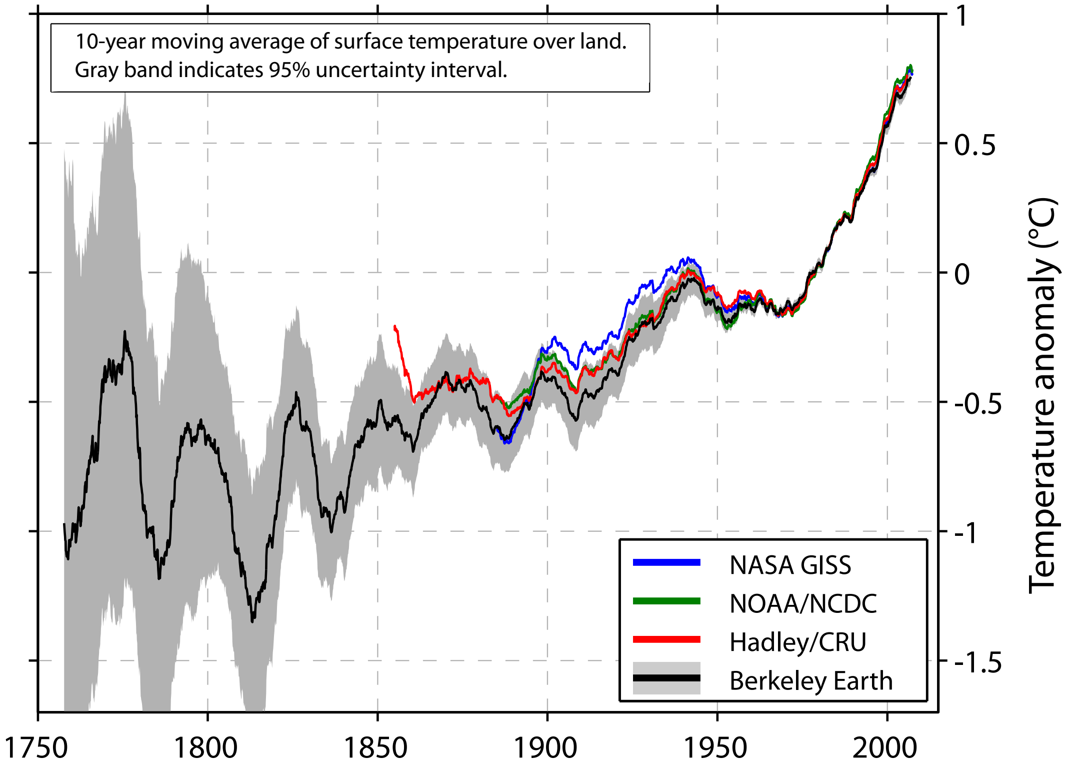

Figure 4: Global land surface temperature anomalies since 1750.[21]

Smoothed with a 10-year filter.

ing from 1910 to 1940 and the grand hiatus of 1940–1975. Further, there is a secular warming trend at least since 1800 (and possibly as long as 400 years) that cannot be explained by carbon dioxide, and is only partly explained by volcanic eruptions.

Evidence that the climate models are not fit for the purpose of identifying with high confidence the relative proportions of natural and human causes to the 20th century warming is as follows:

- substantial uncertainties in equilibrium climate sensitivity (ECS)
- the inability of GCMs to simulate the magnitude and phasing of natural internal variability on decadal-to-century timescales
- the use of 20th century observations in calibrating/tuning the GCMs
- the failure of climate models to provide a consistent explanation of the early 20th century warming and the mid-century cooling.

4 Are GCMs a reliable tool for predicting climate change?

The IPCC has made the dire prediction that we can expect 4°C or more of warming by the end of the 21st century if carbon dioxide emissions are not reduced.

Projections of warming for the early 21st century

In assessing the credibility of this claim, we should first assess how the GCMs have performed in simulating the early 21st century climate variability. Chapter 11 of the IPCC Fifth Assessment Report[24] focused on near-term climate change, through to 2035. Figure 5 compares GCM projections with recent observations of global surface temperature anomalies.

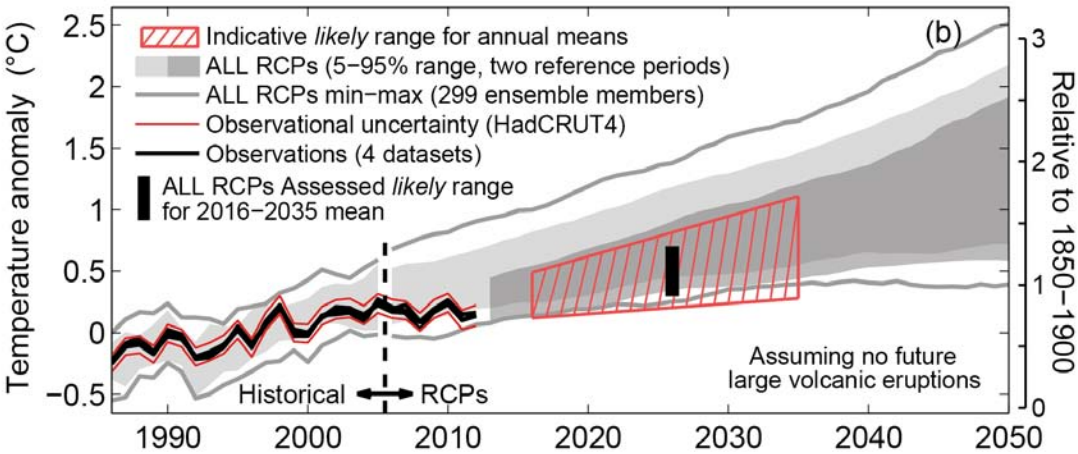

Figure 5: Comparison of CMIP5 climate model simulations of global surface temperature anomalies with observations through 2014 (HadCRUT4). Source: Figure 11.25 of the IPCC AR5.

The observed global temperatures for the past decade are at the bottom bound of the 5–95% envelope of the CMIP5 climate model simulations. Overall, the trend in the climate model simulations is substantially larger than the observed trend over the past 15 years. Regarding projections for the period 2015–2035, the 5–95% range for the trend of the CMIP5 climate model simulations is 0.11–0.41°C per decade. The IPCC then cites 'expert judgment' as the rationale for lowering the projections (indicated by the red hatching in Figure 5):

> However, the implied rates of warming over the period from 1986–2005 to 2016–2035 are lower as a result of the hiatus: 0.10°C–0.23°C per decade, suggesting

the AR4 assessment was near the upper end of current expectations for this specific time interval.

This lowering of the projections relative to the results from the raw CMIP5 model simulations was done based on the expert judgment that some models are too sensitive to anthropogenic (carbon dioxide and aerosol) forcing. IPCC author Ed Hawkins, who originally created the above figure, has updated it with surface temperature observations through to the end of 2015: The spike in global temperatures from the 2015

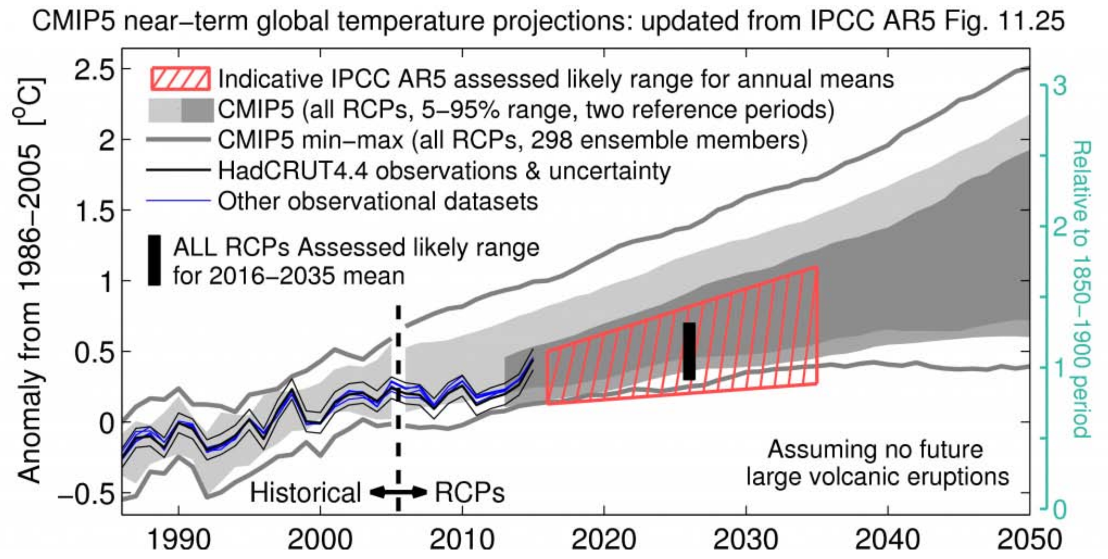

Figure 6: Comparison of CMIP5 climate model simulations of global surface temperature anomalies with observations through 2015 (HadCRUT4). Updated from Figure 11.25 of the IPCC AR5.[25]

El Niño helps improve the agreement between models and observations, but not by very much. The 2015 temperature spike does not even reach the midpoint of the climate model projections, whereas the 1998 El Niño temperature spike was at the top of the envelope of temperature predictions. So far in the 21st century, the GCMs are warming, on average, about a factor of 2 faster than the observed temperature increase. The reason for the discrepancy between observations and model simulations in the early 21st century appears to be caused by a combination of inadequate simulations of natural internal variability and oversensitivity of the models to increasing carbon dioxide (ECS).

Projections for the end of the 21st century

Climate model projections of global temperature change at the end of the 21st century are driving international negotiations on carbon dioxide emissions reductions, under the auspices of the UN Framework Convention on Climate Change.[26] Figure 7 shows climate model projections of 21st century warming. RCP8.5 is an extreme scenario of increasing emissions of greenhouse gases, whereas RCP2.6 is a scenario where emissions peak around 2015 and are rapidly reduced thereafter. Under the

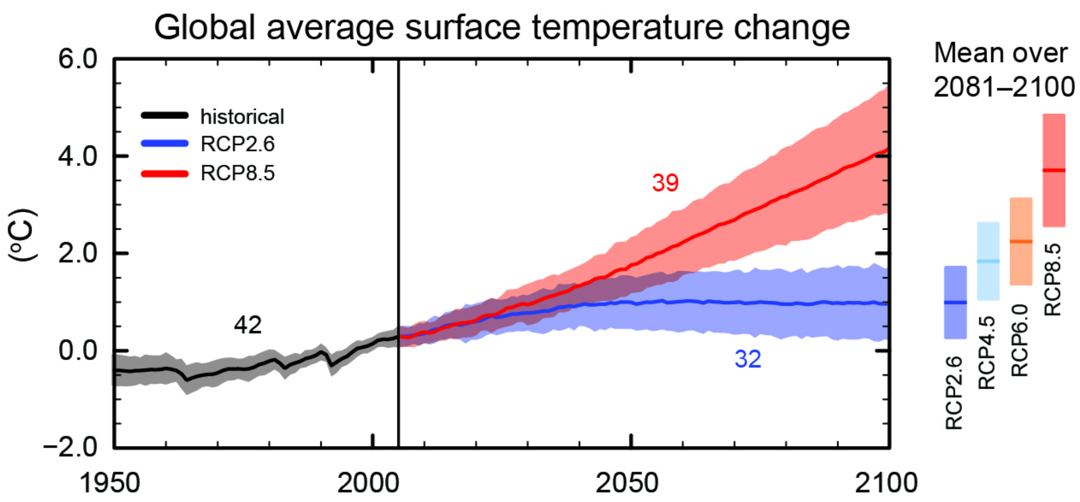

Figure 7: Figure SPM.7 of the IPCC AR5 WG1.

CMIP5 multi-model simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081-2100 are given for all RCP scenarios as colored vertical bars.

RCP8.5 scenario, the CMIP5 climate models project continued warming through the 21st century that is expected to surpass the 'dangerous' threshold of 2°C warming as early as 2040. It is important to note that the CMIP5 simulations only consider scenarios of future greenhouse gas emissions – they do not include consideration of scenarios of future volcanic eruptions, solar variability or long-term oscillations in the ocean. Russian scientists[27] argue that we can expect a Grand Solar Minimum (contributing to cooling) to peak in the middle of the 21st century.

While the near-term temperature projections were lowered relative to the CMIP5 simulations (Figure 5), the Summary for Policymakers of the IPCC Fifth Assessment[28] states with regards to extended-range warming:

> The likely ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near-term (2016-2035) global mean surface temperature change that is lower than the 5-95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding.

There is a troubling internal inconsistency in the Working Group I * report of the IPCC Fifth Assessment: it concluded that there is a substantial uncertainty in climate sensitivity and it accordingly lowered the official temperature projections for 2016–2035 relative to the climate model projections. However, despite this recognition that the GCMs are running too hot, for the remaining period out to 2100, it retained the climate model predictions unchanged.

Even more troubling is that the IPCC Working Group III report on the 'Mitigation of Climate Change' conducted its entire analysis assuming a 'best estimate' of ECS of 3.0°C. The scientific assessment had declined to select a 'best estimate' for ECS, owing to the discrepancy between GCM estimates and observations; the warming of the atmosphere is about half the magnitude of the climate model estimates, so the CMIP5 models produce warming that is nominally twice as large as the lower values of climate sensitivity would produce. No account is made in these projections of 21st century climate change for the substantial uncertainty in climate sensitivity that is acknowledged by the IPCC.

The IPCC's projections of 21st century climate change explicitly assume that carbon dioxide is the control knob for global climate. Climate model projections of the 21st century climate are not convincing because of:

- failure to predict the warming slowdown in the early 21st century
- inability to simulate the patterns and timing of multidecadal ocean oscillations
- lack of account for future solar variations and solar indirect effects on climate
- neglect of the possibility of volcanic eruptions that are more active than the relatively quiet 20th century
- apparent oversensitivity to increases in greenhouse gases

5 Summary

There is growing evidence that climate models are running too hot and that climate sensitivity to carbon dioxide is at the lower end of the range provided by the IPCC. Nevertheless, these lower values of climate sensitivity are not accounted for in IPCC climate model projections of temperature at the end of the 21st century or in estimates of the impact on temperatures of reducing carbon dioxide emissions. The IPCC climate model projections focus on the response of the climate to different scenarios of emissions. The 21st century climate model projections do not include:

- a range of scenarios for volcanic eruptions (the models assume that the volcanic activity will be comparable to the 20th century, which had much lower volcanic activity than the 19th century

* Working Group I is the scientific assessment.

- a possible scenario of solar cooling, analogous to the solar minimum being predicted by Russian scientists
- the possibility that climate sensitivity is a factor of two lower than that simulated by most climate models
- realistic simulations of the phasing and amplitude of decadal- to century-scale natural internal variability

The climate modelling community has been focused on the response of the climate to increased human caused emissions, and the policy community accepts (either explicitly or implicitly) the results of the 21st century GCM simulations as actual predictions. Hence we don't have a good understanding of the relative climate impacts of the above or their potential impacts on the evolution of the 21st century climate.

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GWPF BRIEFINGS

1	Andrew Turnbull	The Really Inconvenient Truth or 'It Ain't Necessarily So'
2	Philipp Mueller	The Greening of the Sahel
3	William Happer	The Truth about Greenhouse Gases
4	Gordon Hughes	The Impact of Wind Power on Household Energy Bills
5	Matt Ridley	The Perils of Confirmation Bias
6	Philipp Mueller	The Abundance of Fossil Fuels
7	Indur Goklany	Is Global Warming the Number One Threat to Humanity?
8	Andrew Montford	The Climate Model and the Public Purse
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10	Andrew Montford	Precipitation, Deluge and Flood
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12	Madhav Khandekar	Floods and Droughts in the Indian Monsoon
13	Indur Goklany	Unhealthy Exaggeration
14	Susan Crockford	Twenty Reasons not to Worry about Polar Bears
15	Various	The Small Print
16	Susan Crockford	The Arctic Fallacy
17	Indur Goklany	The Many Benefits of Carbon Dioxide
18	Judith Curry	The Climate Debate in the USA
19	Indur Goklany	The Papal Academies' Broken Moral Compass
20	Donoughue and Forster	The Papal Encyclical: a Critical Christian Response
21	Andrew Montford	Parched Earth Policy: Drought, Heatwave and Conflict
22	David Campbell	The Paris Agreement and the Fifth Carbon Budget
23	Various	The Stern Review: Ten Years of Harm
24	Judith Curry	Climate Models for the Layman

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