

Commentary

Cascading uncertainty in climate change models and its implications for policy

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Climate scientists face a serious public image problem because the next round of climate models they are working on are destined to produce a *wider* rather than a *smaller* range of uncertainty. To the public and policymakers, it will look as if the scientific understanding of climate change is becoming less rather than more clear, particularly as there will be a deliberate attempt by lobbyists and parts of the media to portray the science in this way. There is a need to communicate the fundamental strengths and weaknesses of climate modelling as an essential tool to allow us to understand the consequences of our actions and to develop appropriate policy. We need to demonstrate that with greater knowledge comes greater uncertainty but also greater transparency and confidence in our knowledge. New communications strategies that do not solely rely on the 'weight of evidence' argument but instead aim to win hearts and minds are required. New policy approaches combining win-win solutions are required if issues of climate change mitigation and adaptation are to be tackled.

KEY WORDS: climate change policy, climate models, uncertainty

The next Intergovernmental Panel on Climate Change (IPCC) major assessment of climate science is due to be released in 2013, and will include climate models containing a significant increase in our understanding of complex climate processes. However, these models will have a *wider* rather than smaller range of scientific uncertainty. Scientists need to face up to this, and develop a plan of how to explain uncertainty to avoid climate deniers suggesting that the science is fundamentally wrong. Above all, the public and policymakers need be convinced that climate models have reached their current limit and must stop waiting for further certainty or persuasion, but should start developing appropriate mitigation and adaptation policies around the world.

But for the public and policymakers to move beyond questioning the underlying physics they need to have a greater appreciation of why these numerical models have reached a limit. First, models are not reality. It may sound strange to have to state this but it is a fundamental point which is regularly ignored. Second, there are intrinsic problems with modelling natural systems (Cartwright 1983). This is because it is impossible to truly verify or validate the numerical

models as they are never closed systems and results are never unique (Oreskes *et al.* 1994). This is particularly true of climate models because despite being based on fundamental physical equations they still require many parameters that are incompletely known (Oreskes *et al.* 2010).

One of these variables is the accumulation of greenhouse gases and aerosols in the atmosphere by the end of the century, which is an essential input to the models. These projections are based on economic models, which attempt to predict global fossil fuel use over 100 years given extremely broad assumptions about how integrated and green the global economy will become (IPCC 2000; van Vuuren *et al.* 2011). The original IPCC reports used simplistic assumption of greenhouse gas emissions over the next 100 years. From 2000 onwards the climate models used the Special Report on Emission Scenarios (SRES; IPCC 2000). The next generation of climate model results to be published in the 2013 IPCC Science Report will use the new representative concentration pathways (RCPs) which consider a much wider variable input to the social-economic models, including population, land use, energy

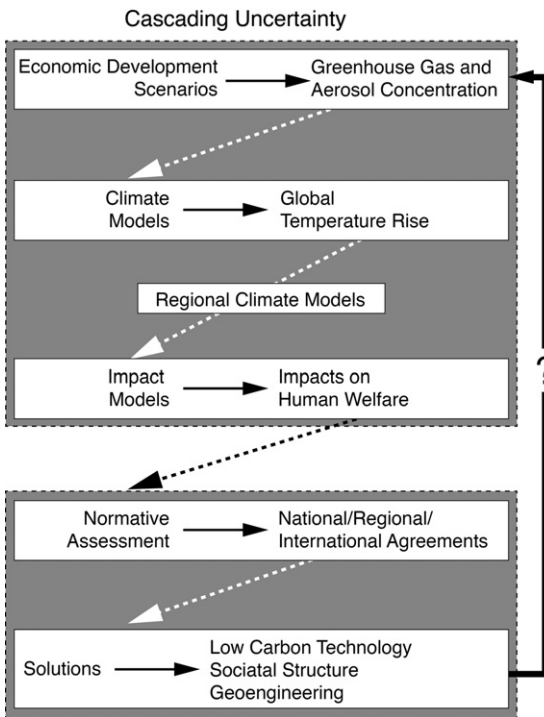


Figure 1 Estimations of climate change impact and societal response based on models containing increasing uncertainty. Solid lines are modelled outputs while white dotted lines are inputs to the next layer of models
 Source: Adapted and expanded from Hillerbrand and Ghil (2008)

intensity, energy use and regional differentiated development. However the new RCPs mean that comparison of the 2013 IPCC results will be difficult with the IPCC 2001 and 2007 outputs, which used the SRES. These scenarios are just the start of the cascade of uncertainty shown in Figure 1.

In the most recent IPCC assessment, released in 2007, the greenhouse gas scenarios were then input into about 20 general circulation models (GCMs). Each of the models has their own independent design and parameterisations of key processes. For example, how to model the positive and negative feedbacks from clouds. Clouds are one of the largest uncertainties in climate models as they increase the global reflection of solar radiation up to 30%, reducing the amount of sunlight absorbed by the Earth. But this cooling is offset somewhat by the greenhouse effect of clouds, which reduces the net loss of heat from the Earth. The independence of each model is important, as some confidence may be derived from multiple runs on different models providing similar future climate predictions. While the differences between the models can help us to learn about their individual limitations and advan-

tages. Within the IPCC, due to political expediency, each model and its output is assumed to be equally valid. This is despite the fact that some are known to perform better than others when tested against reality provided by the historic and palaeoclimate records. This difference will be exacerbated in the 2013 IPCC assessment as some models have greater spatial resolution while others do not. Moreover, as discussed by Palmer (2012), we understand uncertainty within a single model but the notion of quantifying uncertainty from many models currently lacks any real theoretical background or basis.

The outputs from these GCMs are then used to drive more detailed regional climate models to project more local environmental variations. Down-scaling is a huge problem recognised in the modelling community (IPCC 2007b). This is because precipitation is spatially and temporally highly variable but essential to model if human impacts are to be predicted (Oreskes *et al.* 2010). Ultimately the cascade of uncertainty leads to a huge range of potential future events at a regional level that are in some cases contradictory. For example, detailed hydrological modelling of the Mekong River Basin using climate model input from just a single GCM (the Met Office HadCM3) led to projected future changes in annual river discharge ranging from a decrease of 5.4% to an increase of 4.5% (Kingston *et al.* 2011). Changes in predicted monthly discharge are even more dramatic, ranging from -16% to +55%. Advising policymakers becomes extremely hard when the uncertainties do not even allow one to tell if the river catchment system in the future will have more or less water. But there may be key communication lessons that we could learn from the way other scientists communicate risk, for example, with earthquake risk the public and policymakers have become used to the idea of probability when it comes to timing and magnitude.

The projected regional climate changes are then used as a basis for so-called impact models that attempt to estimate the effect on the quality of human life (Barker 2008). The scale of impact of climate change is, however, driven more by the relative resilience of the society affected than the magnitude of change. The most advanced of these socioeconomic models determine the monetary costs arising both in market and non-market sectors. But these models fail to adequately account for many aspects of human suffering possibly caused by climate change, as they evaluate the impact of climate change on human welfare purely in monetary terms (Stern 2007). Whereas money can be lent, exchanged, traded or even gain interest, an individual's welfare and life cannot. Moreover, despite continued arguments between economists, future losses are discounted at a fairly arbitrary rate (Stern 2007).

Above we have considered mean state changes such as river discharge. The single biggest problem with impact models, however, is their inability to

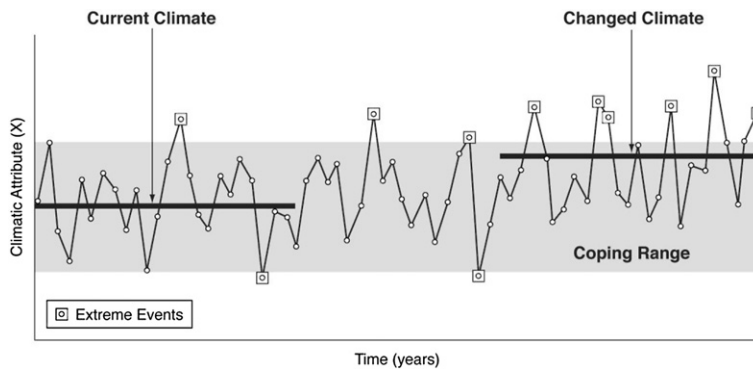


Figure 2 Climate change, society's weather coping range, and extreme events
 Source: Adapted from Maslin (2009)

predict extreme events, though a recent IPCC report tries hard to set new foundations for this sort of work (IPCC 2012). This is because we know that humanity can live, survive and even flourish in extreme climates from the Arctic to the Sahara, but problems arise when the predictable extremes of local climate are exceeded. For example, heat waves, storms, droughts and floods in one region may be considered fairly normal weather in another. This is because each society has a 'climatic' coping range, which in effect, is a range of weather that it has evolved historically to deal with. Figure 2 shows the theoretical effect of combining the coping range with climate change. In our present climate, the coping range encompasses nearly all the variation in weather with maybe only one or two significant events causing disruption per year. As the climate moves gently to its new average, if the coping range stays the same then many more extreme events occur. For example, in the historically mild climate of northern Europe, homes are built with central heating but not air-conditioning. As summer temperatures increase and heat waves like 2003 become common, then the coping range of our homes will be exceeded (Maslin 2009). Over 35 000 older people died during the 2003 heat wave due to the inability to deal with high night-time temperatures. This does not occur in other much hotter developed countries because of the extensive availability of air-conditioning.

Climate change science is also rapidly moving forward and is now attempting to attribute the contribution of anthropogenic climate change to extreme weather events. A few years ago this would be unheard of and the standard communication line was that scientists could not attribute individual weather events to climate change but the event in question may be consistent with what is expected to happen in the future. However, with increased computer power it is possible to run regional climate scenarios with and without the contribution of global warming and

so assess the potential impact on the occurrence of extreme weather events. A discernable contribution of climate change was found for UK Floods in 2000 (Pall *et al.* 2011), the Russian heat wave of 2010 (Otto *et al.* 2012), and the Texan and East African droughts of 2011 (Peterson *et al.* 2012), while none was found for the floods in Thailand in 2011 (Peterson *et al.* 2012). However, this science is still in its infancy and sometimes throws up contradictory studies due to what we exactly mean by anthropogenic climate change contribution. This is shown by two papers related to the Russian heat wave of 2010. Dole *et al.* (2011) concluded that climate change did not contribute to the event while Rahmstorf and Coumou (2011) concluded that it had. The apparent mismatch was because the two papers asked different questions (Otto *et al.* 2012). Dole *et al.* (2011) showed that climate change had had little or no effect on the magnitude of the Russian heat wave, while Rahmstorf and Coumou (2011) showed that climate change had increased the frequency at which these events could occur. This demonstrates the importance of scientists and policymakers asking the right questions.

Despite potential limitations with climate models there is still a wide range of views about how useful they are in helping us to understand the future and informing policy. A central debate has emerged between scientists who take the optimistic view suggesting we can model future climate tipping points (Lenton 2011) and those who say we cannot even get the past correct (Valdes 2011). Lenton (2011) tackles potential climate tipping points such as the irreversible melting of the Greenland ice sheet, dieback of the Amazon rainforest and the shift of the West African monsoon. He argues that with more research it will be possible to use models to provide an early warning system as we approach climatic tipping points. Lenton (2011) uses inherent assumptions about bifurcations within critical parts of the climate system and the ability to use the past climate records as a test for

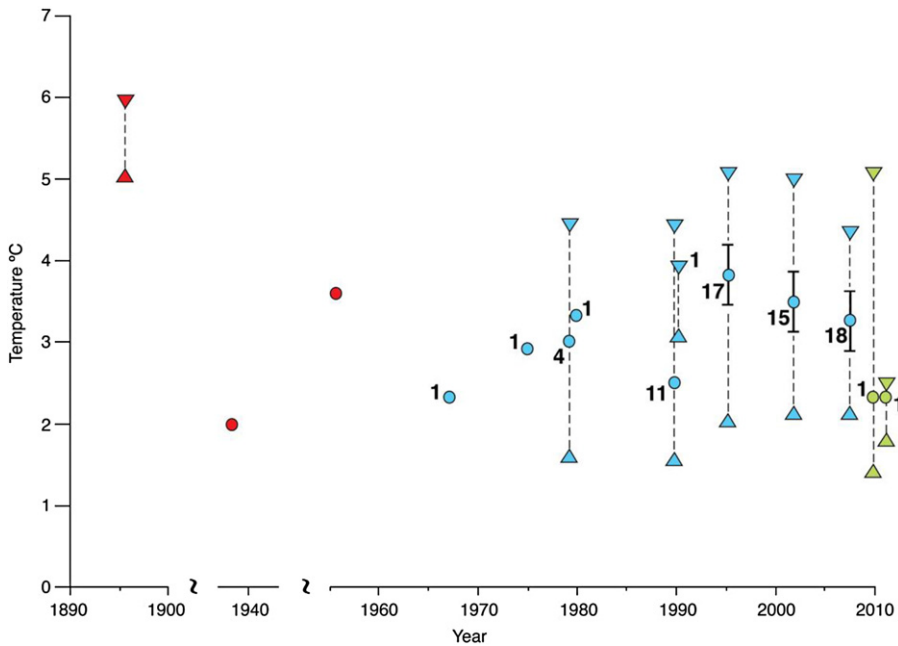


Figure 3 Collation of equilibrium climate sensitivity estimates, which represent the equilibrium global temperature reached with a doubling of atmospheric carbon dioxide (see Table 1). Red shows estimates using just equations; blue shows when climate models have been used and how many; and green shows when palaeoclimate records have been used to provide the estimate. Circles are the best estimate and triangles represent the full published potential range
 Source: Adapted from Maslin and Austin (2012)

these tipping points. In contrast, Valdes (2011) argues that the current IPCC models cannot simulate abrupt climate change. When tested against four major past climate changes, for two of them, the models did not even get the basic climate prior to the shift correct, and for the other two, climate forcing up to 10 times greater than natural were required to get the abrupt shift. His conclusion was that climate models are too stable and are built not to fail. These are two very different views by respected scientists, but it is the former view that is the most worrying and seems to imply we have forgotten all the lessons learnt about the limits of knowledge from chaos and complexity theory.

This discussion does not mean that climate models are useless. The present models are clearly able to reproduce natural climate variability over the past 150 years. They have provided an essential test of the theoretical link between CO₂ and global temperatures, supporting the extensive experimental and palaeoclimate work. They provide an insight into the possible climate of the future and clear choices about what future we would like to have. This vision of the future has been incredibly stable. For example, the predicted global temperature rise resulting from a doubling of CO₂ in the atmosphere has not changed much in over 20 years (Figure 3 and Table 1; Knutti

and Hegerl 2008). Yet when Schmittner *et al.* (2011) published a slightly lower value, the BBC declared 'Climate sensitive was overestimated' despite significant criticisms of the study and the fact it still fell within the range of all the IPCC reports. The uncertainties around future projections are because of the complexity of positive and negative feedback within the climate system, and represent our ability to understand each process. The consistency of predictions over decades leads to an increase in our confidence because, despite the uncertainty, the basic projections have not changed (Figure 3). It is these key points that need to be emphasized and clearly communicated when the next IPCC assessment is published.

The climate models, or as some groups are now referring to them, 'climate simulators' in the IPCC fifth assessment will include some significant improvements. Many of the models contain better representation of atmospheric chemistry, aerosol processes and the carbon cycle, including land vegetation feedbacks, while the cascade of uncertainties inherent to modelling work will remain much the same. Many of the models will have a small increase in spatial resolution. The models will also focus on decadal forecasts to help us understand the internal variability of the climate (Cane 2011). There will also be separate chapters dealing with near-term climate up to 2050

Table 1 Review of equilibrium climate sensitivity (ECS) estimates, which represent the equilibrium global temperature reached with a doubling of atmospheric carbon dioxide

Year	Source	ECS (°C)	Range (°C)	Models used
1896	Arrhenius	No figure given	4.95–6.05	Equations
1938	Callendar	2.0	Not given	Equations
1956	Plass	3.6	Not given	Equations
1967	Manabe and Weatherald	2.3	Not given	1
1975	Manabe and Weatherald	2.93	Not given	1
1979	Charney <i>et al.</i>	3.0	±1.5	4
1979	Ramanthan <i>et al.</i>	3.29 – this is from the annual model	No range is given	1
1990	Lorius <i>et al.</i>	Range only	3.0–4.0	1
1990	IPCC first assessment report	2.5	1.5–4.5	11
1995	IPCC second assessment report	3.8 ± 0.78	1.9–5.2	17
2001	IPCC third assessment report	3.5 ± 0.92	2.1–5.1	15
2005	Frame <i>et al.</i>	2.4	1.4–4.1	
2006	Forster and Gregory		1–4.1	Equations
2007	Royer <i>et al.</i>		1.6–5.5	Palaeo-data
2007a	IPCC fourth assessment report	3.26 ± 0.69	2.1–4.4	18
2010	Köhler <i>et al.</i>	2.3	1.3–5.2	Palaeo-data
2011	Schmittner <i>et al.</i>	2.3	1.7–2.6	1 model with palaeo-data constraints

Note that the Schmittner *et al.* (2011) estimate is thought to be too low as they assume the Last Glacial Maximum was globally only 3.5°C cooler not 5.8 ± 1.4°C as found by others (e.g. Schnieder Von Deimling *et al.* 2006)

and climate post 2100. There is also very little change in equilibrium climate sensitivity to doubling of atmospheric CO₂. The uncertainties around future projections may increase by up to 20%, but this is because of our greater understanding of the processes and our ability to quantify that knowledge. Rowlands *et al.* (2012) recently explored the amount of uncertainty inherent in complex models by running one specific model through nearly 10 000 simulations (as opposed to the usual handful of runs that can usually be managed). While his average results matched well with previous IPCC projections, Rowlands found that more extreme results, including warming of up to 4°C by 2050, were just as likely. That uncertainty was masked in the IPCC fourth assessment by the fact that complex models are not usually put through their paces so thoroughly; as computing power becomes more accessible, that 'hidden' uncertainty will become more obvious.

IPCC needs to be aware of the effects of our greater understanding of uncertainties. It needs to design a communication strategy that allows a clear demonstration of the science (Corfee-Morlot *et al.* 2007) and for once be prepared for the inevitable backlash from those who wish to misunderstand the science. IPCC needs to appreciate the scale and funding these groups and individuals represent. For example, a quick look at the top 10 'global warming' books on amazon.co.uk (accessed 2 September 2012) showed that 6 out of the top 10 were by climate change deniers. Interestingly, only 2 out of the top 10 books using 'climate change' in

the title were written by climate change deniers. What is clear is that one part-time 'media person' was not enough to deal with the so-called 'climate-gate' or 'Himalayan-gate' media events. The IPCC now has two full-time media experts but compare this to Tesco UK, which has a whole 'government department' that is aimed at lobbying just the UK government. The IPCC has also been offered free support by many of the world's leading PR/advertising/campaign companies but has turned much of it down. This is a great shame given the communications challenge of climate change and the new IPCC 2013 Science Report. The IPCC must stop approaching the communication challenge from a science perspective as it is clear that 'scientific weight of evidence' is not the issue; if it were then the battle would have been over long ago. Rather it is about vestige interests both politics and business that do not want to have to deal with the fact that our pollution is changing the climate and we should do something about it. At a more worrying level, it is also about how science is now seen and understood in the USA and the UK. Over the past 25 years scientific issues have become akin to a belief system with questions like 'do you believe in evolution' or 'do you believe in climate change' becoming the norm. Climate change communication is much more about good PR that wins hearts and minds. One novel approach could be to define uncertainty in terms of when the planet will hit a certain temperature. This approach has recently been used by Joshi *et al.* (2011), who showed that the political expedient 2°C limit will



Figure 4 Comic from the United States news publication *USA Today*, 2009

be reached between 2040 and 2100 depending on our emissions pathway and which model is used. This ‘when’ not ‘if’ approach is a very powerful when illustrating the impacts of future climate change.

In the face of scientific uncertainty, various philosophies for decisionmaking have arisen. Each has flaws. The precautionary principle states that action should be taken against worst-case scenarios, ‘just in case’. This is problematic as it does not take into account that acting, as well as not acting, may yield unacceptable consequences. Cost–benefit analyses attempt to take this into account by totalling the sum impacts of different actions or non-actions. But there are serious problems in accounting for all possible costs, and giving them a numerical value. Debates arise about whether the cost to our offspring should count for less than the costs to today’s generation (known as ‘discounting the future’), and about the (perhaps variable) value of human life. Expected utility theory, a tool that balances risk against reward using probabilistic mathematical functions, requires assumptions about the likely impacts on human welfare and assumes a moral focus on the majority rather than the individual (Hill-erbrand and Ghil 2008).

However, uncertainty rarely stops politicians making decisions, and in the case of climate change, public opinion and scientific uncertainty seem to be used as excuses for inaction. For example, politicians used to say ‘we need to wait until scientists prove that mankind is causing climate change’. That hurdle has passed; now they have moved on to ‘we need to wait until scientists can tell us exactly what will happen, and the costs of inaction’, or ‘we need to wait for public opinion to be behind action’. As I hope I have demonstrated above, the former will never occur because the modelling can never provide that level of

certainty. The latter is a slight of hand as in no other area do politicians assume the need for public support; for example, from wars to bank bailouts, from taxation to healthcare reforms.

Greater knowledge and better models will always be desirable but they are not the panacea to cure political and public reticence to act on climate change. So despite the increased defined uncertainty within climate models, the increased confidence and huge weight of scientific evidence are good enough to tell us what we fundamentally need to know. We need governments to just go ahead and take action, which is exactly what has occurred in the UK, the EU and Mexico with climate change legislation. But, as scientists, we must remember that policymakers have to put climate change in the context of the meta-narratives of the twenty-first century, which include global economic stability, alleviating global poverty and global security (e.g. Stern 2007; Adger 2006; Barnett and Adger 2007). This is because, despite the seriousness of climate change and the worry of what might happen in 10, 20 or 50 years time, it seems rather naïve when 8 million children die needlessly each year, 800 million people go to bed hungry each night and 1000 million people still do not have regular access to clean safe drinking water (Kovats *et al.* 2005; Costello *et al.* 2009).

Despite the actions of individual countries and regions, there is still a need for a legally binding international agreement. Once these are forthcoming there would still need to be sophisticated political solutions at all levels; from the binding international agreement to regional, national and local policies (Maslin and Scott 2011). This multi-level governance is essential as it provides redundancy in the system and acts as a regulatory safety net if higher-level poli-

cies break down or are gamed. For example, the UN Clean Development Mechanism (CDM) gives credits for projects involving the capture of industrial gases (hydrofluorocarbons or HFCs) and has regrettably been easy to game. The regulation has created a perverse incentive for companies to produce more HCFC-22, a refrigerant and powerful greenhouse gas being phased out under the Montreal Protocol, in return for windfall profits for capturing the HFC-23 by-product from its production. The European Commission concluded in 2011 that production of HCFC-22 could be higher today than it would have been in the absence of CDM activity.

Action on climate change, therefore, should always contain an element of win-win. For example, supporting a huge increase in renewable energy not only reduces emissions but helps to provide energy security by reducing the reliance on imported oil, coal and gas (Bradshaw 2010). Reduced deforestation and reforestation should not only draw down CO₂ from the atmosphere but help to retain biodiversity, stabilise soils and provide livelihoods for local people via carbon credits. Measures that reduce car use will increase walking and cycling, which in turn reduce obesity and heart attacks (Haines *et al.* 2009). No one can object to creating a better world, even if we are extremely lucky and the scale of climate change is on the low end of all projections. This point was beautifully illustrated by a cartoon published in *USA Today* in 2009 (see Figure 4).

Predicting the future is extremely hard. Climate scientists' projections of the future and their associated uncertainties are an essential tool to allow us to understand the consequences of our actions. Climate scientists need to communicate the fundamental strengths of the science and why estimations of uncertainties demonstrate the transparency of our knowledge. We do not need to demand impossible levels of certainty from the models to envisage a better safer future.

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References

- Adger N** 2006 Vulnerability *Global Environmental Change* 16 268–81
- Arrhenius S** 1896 On the influence of carbonic acid in the air upon the temperature of the ground *Philosophical Magazine and Journal of Science* 5 237–76
- Barker T** 2008 The economics of avoiding dangerous climate change: an editorial essay on the Stern Review *Climatic Change* 89 173–94
- Barnett J and Adger W N** 2007 Climate change, human security and violent conflict *Political Geography* 26 639–55
- Bradshaw M** 2010 Global energy dilemmas: a geographical perspective, *The Geographical Journal* 176 275–90
- Callendar G S** 1938 The artificial production of carbon dioxide and its influence on temperature *Quarterly Journal of the Royal Meteorological Society* 64 223–40
- Cane M** 2011 Climate science: decadal predictions in demand *Nature Geosciences* 3 231–2
- Cartwright N** 1983 *How the laws of physics lie* Clarendon Press, Oxford
- Charney J G, Arakawa A, Baker D J, Bolin B, Dickson R E, Goody R M, Leith C E, Stommel H M, Wunsch C I** 1979 *Carbon dioxide and climate: a scientific assessment* Report of an Ad Hoc study group on carbon dioxide and climate, Woods Hole, MA 23–27 July 1979, to the Climate Research Board, Assembly of Mathematical and Physical Sciences, National Research Council
- Corfee-Morlot J, Maslin M A and Burgess J** 2007 Climate science in the public sphere *Philosophical Transactions of the Royal Society A* 365 2741–76
- Costello A, Abbas M, Allen A, Ball S, Bell S, Bellamy R, Friel S, Groce N, Johnson A, Kett M, Lee, M, Levy C, Maslin M, McCoy, D, McGuire, B, Montgomery H, Napier D, Pagel C, Patel J, de Oliveira J, Redclift N, Rees H, Rogger D, Scott J, Stephenson J, Twigg J, Wolff J, Patterson C** 2009 Managing the health effects of climate change *The Lancet* 373 1693–733
- Dole R, Hoerling M, Perlwitz J, Eischeid J, Pegion P, Tao Zhang T, Xiao-Wei Quan X-W, Xu T, Murray D** 2011 Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters* 38 L06702
- Forster P M and Gregory J M** 2006 The climate sensitivity and its components diagnosed from earth radiation budget data *Journal of Climate* 19 39–52
- Frame D J, Booth B B B, Kettleborough J A, Stainforth D A J, Gregory J M, Collins M and Allen M R** 2005 Constraining climate forecasts: the role of prior assumptions *Geophysical Research Letters* 32 L09702
- Haines A, McMichael A, Smith K, Roberts I, Woodcock J, Markandya A, Armstrong B G, Campbell-Lendrum D, Dangour A, Davies M, Bruce N, Tonne C, Barrett M, Wilkinson P** 2009 Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers *The Lancet* 374 2104–14
- Hillerbrand R and Ghil M** 2008 Anthropogenic climate change: scientific uncertainties and moral dilemmas *Physica D* 237 2132–8
- IPCC** 1990 *Climate change* The IPCC Scientific Assessment of Working Group I **Houghton J T, Jenkins G J and Ephraums J J** eds Cambridge University Press, Cambridge, UK
- IPCC** 1995 *Climate change 1995: the science of climate change* Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change **Houghton J T, Meira Filho L G, Callander B A, Harris N, Kattenberg A and Maskell K** eds Cambridge University Press, Cambridge, UK

- IPCC 2000** *Emissions scenarios* **Nakicenovic N and Swart R** eds Cambridge University Press, Cambridge, UK
- IPCC 2001** *The scientific basis* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change **Houghton J T, Ding Y, Griggs D J, Noguer M, van der Linden P J, Dai X, Maskell K and Johnson C A** eds Cambridge University Press, Cambridge, UK
- IPCC 2007a** *The physical science basis* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change **Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M and Miller H L** eds Cambridge University Press, Cambridge, UK
- IPCC 2007b** *Impacts, adaptation and vulnerability* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change **Parry M L, Canziani O F, Palutikof J P, van der Linden P J and Hanson C E** eds Cambridge University Press, Cambridge, UK
- IPCC 2012** Summary for policymakers in **Field C B, Barros V, Stocker T, Qin D, Dokken D K, Ebi K L, Mastrandrea M D, Mach K J, Plattner G K, Allen S K, Tignor M and Midgley P M** eds *Managing the risks of extreme events and disasters to advance climate change adaptation A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* Cambridge University Press, Cambridge, UK and New York 3–21
- Joshi M, Hawkins E, Sutton, R, Lowe J, Frame D** 2011 Projections of when temperature change will exceed 2°C above pre-industrial levels *Nature Climate Change* 1 407–12
- Kingston D G, Thompson J R, Kite G** 2011 Uncertainty in climate change projections of discharge for the Mekong River Basin *Hydrology and Earth System Science* 15 1459–71
- Knutti R and Hegerl G C** 2008 The equilibrium sensitivity of the Earth's temperature to radiations changes *Nature Geosciences* 1 735–42
- Köhler P, Bintanja R, Fischer H, Joos F, Knutti R, Lohmann G and Masson-Delmotte V** 2010 What caused Earth's temperature variations during the last 800,000 years? Data-based evidence on radiative forcing and constraints on climate sensitivity *Quaternary Science Reviews* 29 129–45
- Kovats R S, Campbell-Lendrum D and Matthies F** 2005 Climate change and human health: estimating avoidable deaths and disease *Risk Analysis* 25 1409–18
- Lenton T** 2011 Early warning of climate tipping points *Nature Climate Change* 1 201–9
- Lorius C, Jouzel J, Raynaud D, Hansen J and Treut H L** 1990 The ice-core record: climate sensitivity and future greenhouse warming *Nature* 347 139–45
- Manabe S and Wetherald R T** 1967 Thermal equilibrium of the atmosphere with a given distribution of relative humidity *Journal of Atmospheric Science* 24 241–59
- Manabe S and Wetherald R T** 1975 The effects of doubling the CO₂ concentration on the climate of a general circulation model *Journal of Atmospheric Sciences* 32 3–15
- Maslin M** 2009 *Global warming a very short introduction* 2nd ed Oxford University Press, Oxford
- Maslin M A and Austin P** 2012 Uncertainty: climate models at their limit? *Nature* 486 183–4
- Maslin M A and Scott J** 2011 Carbon trading needs a multi-level approach? *Nature* 475 445–7
- Oreskes N, Shrader-Frechette K, Belitz K** 1994 Verification, validation, and confirmation of numerical models in the Earth Sciences *Science* 263 641–6
- Oreskes N, Smith L, Stainforth S** 2010 Adaptation to global warming: do climate models tell us what we need to know *Philosophy of Science* 77 1012–28
- Otto F E L, Massey N, van Oldenborgh G, Jones R and Allen M R** 2012 Reconciling two approaches to attribution of the 2010 Russian heat wave *Geophysical Research Letters*. 39 L04702
- Pall P, Aina T, Stone D, Stott P, Nozawa T, Hilberts A, Lohmann D and Allen M R** 2011 Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000 *Nature* 470 382–5
- Palmer T N** 2012 Towards the probabilistic Earth-system simulator: a vision for the future of climate and weather prediction *Quarterly Journal of the Royal Meteorological Society* 138 841–61
- Peterson T C, Stott P A and Herring S** eds 2012 Explaining extreme events of 2011 from a climate perspective *Bulletin of the American Meteorological Society* 93 1041–67
- Plass G** 1956 The carbon dioxide theory of climate change *Tellus* VIII 140–54
- Rahmstorf S and Coumou D** 2011 Increase of extreme events in a warming world *Proceedings of the National Academy of Science USA* 108 179059
- Ramanathan V, Lian M S and Cess R D** 1979 Increased atmospheric CO₂: zonal and seasonal estimates of the effect on the radiation energy balance and surface temperature *Journal of Geophysical Research* 84 4949–58
- Rowlands D J, Frame D J, Ackerley D, Aina T, Booth B B, Christensen C, Collins M, Faull N, Forest C, Grandey B, Gryspeerdt E, Highwood E, Ingram W, Knight S, Lopez A, Massey, N, McNamara F, Meinshausen N, Piani C, Rosier S, Sanderson B M, Smith L A, Stone D, Thurston M, Yamazaki K, Yamazaki Y, Allen M R** 2012 Broad range of 2050 warming from an observationally constrained large climate model ensemble *Nature Geosciences* 5 256–60
- Royer D L, Berner R A and Park J** 2007 Climate sensitivity constrained by CO₂ concentrations over the past 420 million years *Nature* 446 530–2
- Schmittner A, Urban N, Shakun J, Mahowald N, Clark P, Bartlein P, Mix A and Rosell-Mele A** 2011 Climate sensitivity estimated from temperature reconstructions of the last glacial maximum *Science* 334 1385–8
- Schneider von Deimling T, Held H, Ganopolski A and Rahmstorf S** 2006 Climate sensitivity estimated from ensemble simulations of glacial climate *Climate Dynamics* 27 149–63 <http://dx.doi.org/10.1007/s00382-006-0126-8>
- Stern N** 2007 *The economics of climate change: the Stern review* Cambridge University Press, Cambridge, UK
- Valdes P** 2011 Built for stability *Nature Geoscience* 4 414–16
- van Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt G, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith S, Rose S** 2011 The representative concentration pathways: an overview *Climatic Change* 109 5–31