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Climate Models

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Overview

Climate computer models are irreplaceable scientific tools to study the climate system and to allow projections of future climate change. They play a major role in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), underpinning palaeoclimate reconstructions, attribution studies, scenarios of future climate change, and concepts such as climate sensitivity and carbon budgets. While models have greatly contributed to the construction of climate change as a global problem, they are also influenced by political expectations. Models have their limits, they never escape uncertainties, and they receive criticisms, in particular for their hegemonic role in climate science. And yet climate models and their simulations of past, present and future climates, coordinated via an efficient model intercomparison project, have greatly contributed to the IPCC's epistemic credibility and authority.

14.1 Introduction

The role of models in IPCC assessment reports cannot be overestimated. Models provide the core content of the IPCC's reports; all assessment reports and their Summaries for Policymakers (SPMs) are illustrated by figures, graphs and maps based on the outputs of climate models. By providing climate simulations that made it possible to distinguish between anthropogenic and natural influences on twentieth-century climate, from the IPCC's Third Assessment Report (AR3, in 2001) onwards, climate models were central for attributing observed climate change to anthropogenic greenhouse gas emissions with high confidence. Models therefore have a political role. They affirm the reality, form and intensity of climate change, but they also shape the IPCC's particular conception of climate change with which governments engage. Conversely, the development of models and the organisation of climate modelling on an international scale has been in large part driven by the need to produce future climate projections for the IPCC.

In this chapter, I explain how climate models are constituted and how they have evolved and become essential instruments for predicting global climate change. I show how the models and scenarios used by the IPCC have been the target of attacks by climate sceptics, have been subject to critical scrutiny by social scientists, and aroused debates among climatologists about research biases, inadequacies and research strategies. I show how the modelling community has organised itself internationally to make climate simulations comparable by building a powerful ‘knowledge infrastructure’ (Edwards, 2010), the Coupled Model Intercomparison Project (CMIP). Finally, I return to the achievements of climate models and their limitations and ask what their new role could be in shaping future directions for the IPCC. The chapter focuses exclusively on climate models (see Box 14.1) and does not consider a different genre of models – Integrated Assessment Models (IAMs) – which are also central to the IPCC’s work; these are discussed in **Chapter 15**.

14.2 Instruments of Globalisation and Prediction

Climate models, originally called General Circulation Models (GCMs), are numerical programs run on computers to produce simulations of the evolution of the atmosphere. The atmosphere is represented by a three-dimensional grid and the computer calculates for each cell and at each time step the variables characterising the atmospheric state (temperature, pressure, wind, humidity and so on) by solving algorithms based on the physics of the atmosphere. GCMs were initially developed from the end of the 1950s on the very first mainframe computers, at first to calculate the weather and, by the mid-1960s, to study climate.

For more than six decades, climate models have kept their original structure while increasing considerably in size – from thousands to millions of lines of computer code. This evolution has been driven by the exponential increase of computing power, by the extension of observation networks, the rise of earth sciences, and by the growing political importance of the climate problem (Weart, 2008). The algorithms of the models have been improved and their spatial resolution increased. Above all, atmospheric circulation models have included more and more phenomena affecting the climate through parametrisations or by coupling with other models. In the 1980s, scientists succeeded in coupling an atmosphere model with a model of the ocean. In the 1990s, climate models gradually encompassed representations of continental surfaces and sea ice and, from the 2000s, aerosols, dynamic vegetation, atmospheric chemistry, land ice and the carbon cycle. Models that include biogeochemical cycles are often referred to

Box 14.1
Varieties of numerical climate models

A wide range of numerical models – i.e., programs run on computers to produce numerical simulations – are used to study the climate system and climate change across multiple temporal and spatial scales.

GCM: General Circulation Model – or, more recently, Global Climate Model. GCMs are computer programs representing the evolution of the atmosphere. They build on the fundamental laws of physics that govern atmospheric dynamics and on more empirical representations of the other processes affecting the atmosphere (absorption of solar radiation, clouds and so on). GCMs are used on a daily basis for weather forecasts, and to simulate the climate over several decades, centuries or millennia – these long simulations being analysed in statistical terms.

AOGCM: Atmosphere-Ocean coupled General Circulation Model. AOGCMs are numerical models consisting of an atmospheric general circulation model coupled with an ocean circulation model – both based on the laws of fluid dynamics.

ESM: Earth System Model. ESMs seek to simulate all relevant aspects of the Earth system and its physical, chemical and biological processes. In practice, ESMs are atmosphere-ocean coupled models incorporating biogeochemical processes such as the carbon cycle. ESMs can also include models of dynamic vegetation, atmospheric chemistry, ocean biogeochemistry, and continental ice sheets.

EMIC: Earth System Models of Intermediate Complexity. EMICs are simplified models compared to ESMs. They have lower spatial resolution and include processes in a more parameterised form. EMICs are used to investigate the climate on long timescales, for example, for simulations of palaeoclimates.

IAM: Integrated Assessment Model. IAMs are large-scale models composed of modules representing environmental, technological, and human systems in a single integrated framework. They model the evolution of the interaction between these systems by integrating contributions from various disciplines (environmental sciences, economics, engineering and so on) to produce quantified scenarios of global socio-economic developments.

Simple models and emulators: Simple models and emulators are heavily parametrised models, quick to run on laptops or even iphones, and tuned to reproduce the responses of more complex models. Emulators in particular are used to transfer knowledge between the IPCC WGI and other Working Groups (WGs).

as Earth-system models (ESMs). Since the creation of the IPCC, the number of climate models in use around the world has grown enormously – even if the development of climate models and ESMs remains largely restricted to developed countries; see Figure 14.1.

Figure 14.1 Countries with climate models.
In dark grey, countries with climate models listed in AR1 and AR6. In light grey, countries with climate models listed in AR6.

Computer models have greatly contributed to imposing a global vision of climate and climate change (Hulme, 2010), a vision central to the work of the IPCC. The global physico-mathematical vision embedded in these models has thus ousted the plural and geographical conception that prevailed previously – regional climates defined as types of weather (Heymann, 2010). Scientific reasons are often put forward to justify this global scale: for example, carbon dioxide molecules emitted at any point mix quickly with the air and integrate the atmospheric circulation on a planetary scale. But other factors have helped to co-produce this global conception in climate science and policy (Miller, 2004): a powerful infrastructure of observational networks (Edwards, 2010); a long-standing internationally organised scientific community; the huge scientific exploration programs of the American military during the Cold War, relayed by worldwide scientific programs and institutions, such as the World Climate Research Program (WCRP).

GCMs – and later ESMs – are the only simulation tools capable of making quantitative projections of future climate. GCMs were used to assess climate change as a result of increased carbon dioxide atmospheric concentrations long before the creation of the IPCC. In 1979, ‘the Charney report’ for the US National Academy of Sciences first calculated from three models the global warming corresponding to a doubling of the atmospheric carbon dioxide level, while recognising considerable uncertainties (National Research Council, 1979).

Models’ ability to integrate many physical factors when making predictions of future climate have given comprehensive climate modelling a hegemonic status in climate science and, similarly, within the IPCC. But models also contain flaws, gaps and uncertainties (Petersen, [2006] 2012), which modellers attempt to characterise and communicate in IPCC reports (see **Chapter 17**). To build confidence in their simulations, modellers devote a large part of their work to validating models against observational data. Validating future climate projections poses a particular challenge. There is no a priori guarantee that a model that reproduces the characteristics of the current or past climate will also perform well in predicting future climate (Oreskes et al., 1994). Climatologists have developed multiple strategies to compare simulations and observations in a statistical way (Guillemot, 2010), comparisons that are widely assessed by the IPCC.

14.3 Tools for Science and for Policy

Climate models have always played a central role in the IPCC, starting with the First Assessment Report (AR1) in 1990. Models generate climate change projections, underpin attribution studies and guide regional impact assessments, which form the substance of the report. They validate essential concepts in the climate debate – such as global mean temperature, the climate sensitivity and the global carbon budget. Conversely, and importantly, the IPCC has a major influence on the development of climate models. Thus, the improvement of model parametrisations or the introduction of new components into ESMs takes into account the need for future climate projections that IPCC reports demand. As with academic disciplines – see **Chapter 12** – the IPCC is active in shaping the creation of knowledge, via its influence on models, institutions, research programs and careers.

Climate models have a crucial role in predicting, evaluating and attributing anthropogenic climate change, and so the results from climate models inform a range of major policy issues. Social scientists have analysed the effects that both scientific and political objectives have on climate modelling. Because climate change is often framed as a problem in which science is assumed to guide policy decisions, political disagreements are frequently transposed to the scientific field (Pielke, 2002; Sarewitz, 2004). Models have often lain at the centre of such disputes. In the 1990s, debates erupted – especially in the United States – about the difficulties of verifying or validating models in a rigorous fashion (Oreskes et al., 1994). Climate sceptics questioned the scientific credibility of climate models by opposing model simulations to ‘sound science’ based on ‘raw data’. Yet historian Paul Edwards has shown that observed data and climate models are interdependent, this relationship being ‘symbiotic’, with each gaining legitimacy from the other (Edwards, 1999).

Social scientists studied how the political stakes of climate change influence modelling practices, highlighting the elements of co-construction in climate models and simulations. They showed how some parts of climate modelling result from negotiations, or from an anticipation by scientists of the needs of policy makers – notably the representation of uncertainties (Shackley & Wynne, 1996), the estimate of climate sensitivity (van der Sluijs et al., 1998), and recourse to flux adjustments (Shackley et al., 1999).

The hegemonic position of models in climate science – and subsequently in the IPCC – prompted critical analysis of the conception of climate change and the future induced by these ‘global kinds of knowledge’ (Hulme, 2010). In 1991, two Indian scholars criticised the accounting of greenhouse gases based on a physical indicator named Global Warming Potential (GWP). By abstracting these gases molecules from their production context, they claimed, climate models do not distinguish survival emissions of the poor – e.g. methane from rice paddies – from the luxury emissions from the rich – e.g. carbon dioxide from cars and planes (Agarwal & Narain, 1991). According to science and technology studies (STS) scholars, this ‘physico-chemical reductionism’ of climate models obscures the social, economic and historical dimensions of greenhouse gas emissions (Demeritt, 2001). Geographical differences and political contexts are erased. Moreover, models' hegemony within climate change research 'reduces the future to climate' – being partly predictable, climate marginalises other environmental or social factors shaping the future (Hulme, 2011a).

Arguing historically that a 'culture of prediction' often gains traction within environmental issues, scholars such as Matthias Heymann have suggested that climate modelling shifted from offering a heuristic approach to understanding climate to offering predictions for decision-making (Heymann & Hundebol, 2017). The central role that models played in IPCC assessment reports was crucial for this shift. Along the same lines, philosophers of science note that due to the multiplicity of processes interacting in climate models, it is almost impossible to link the characteristics of the simulated climate to a particular component of the model. This 'holism', they claim, 'makes analytic understanding of complex models of climate either extremely difficult or even impossible' (Lenhard & Winsberg, 2010: 253). However, some modellers claim conversely that physical understanding is even more necessary in climate modelling, since the future climate cannot be observed (Bony et al., 2013).

The increasing complexity of climate models is partly a consequence of the need to produce climate predictions. Models have evolved by encompassing more and more environmental phenomena (Dahan-Dalmedico, 2010) because they are supposed to integrate all the processes potentially important for future climate. But climate is subject to a huge range of biogeophysical processes, and the relative importance of any single process is not known until its influence has been tested within the climate system. However, according to some climatologists, this race for complexity, encouraged by a logic of expanded instrumentation and greater funding, should not come to the detriment of research on other climate processes whose role in climate change is known to be essential – for example, concerning cloud feedbacks (Bony et al., 2013).

14.4 A Worldwide Research Infrastructure: CMIP

Since the early 2000s, climate change simulations have been standardised and coordinated through the international CMIP. These multi-model datasets, providing the basis for thousands of peer-reviewed papers, have come to play a prominent role in IPCC reports. In 1990, the WCRP first approved the Atmospheric Model Intercomparison Project (AMIP) in order to compare the output of atmospheric GCMs under similar conditions – same simulation period, same boundary conditions, same carbon dioxide concentrations and so on. Most modelling groups took part in the intercomparison, using the computer facilities of the Lawrence Livermore National Laboratory in California. Having shown the capacity of intercomparison projects to coordinate and organise research (Gates et al., 1999), AMIP paved the way to subsequent 'MIP' exercises.

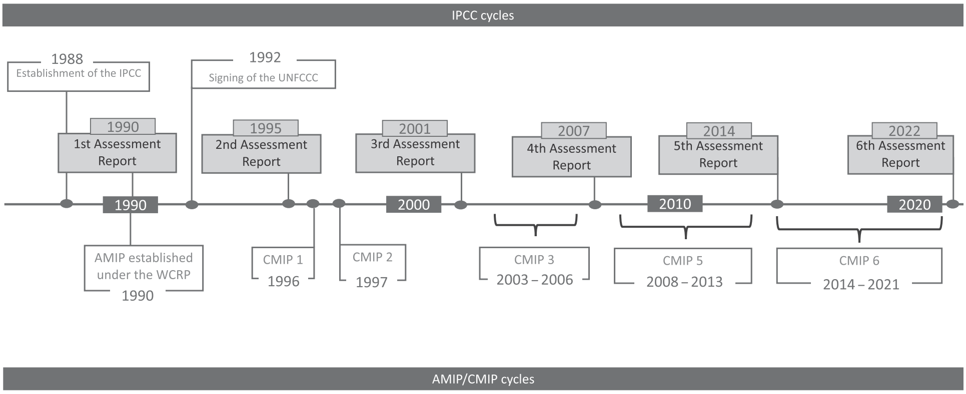

Figure 14.2 Timeline of AMIPs/CMIPs and IPCC assessment cycles.

In 1995, the first phase of the CMIP (CMIP 1) coordinated the comparison of 15 atmosphere-ocean coupled models, soon followed by CMIP 2. CMIP 1 and 2 outputs were included in the IPCC's AR3 report and a few years later, CMIP 3 was designed primarily to provide assessments for the Fourth Assessment Report (AR4), with projections of model simulated climate change under different emission scenarios (Touzé-Peiffer et al., 2020) (see Chapter 15). By 2007, CMIP made outputs from climate change simulations freely available to the scientific community at large, and the simulations for CMIP became synchronised with IPCC reports.

Since 2007, CMIP intercomparison experiments coordinate and pace the work of most modelling groups so as to make it as timely and useful as possible for the IPCC (see Figure 14.2). From CMIP 5 (there was no CMIP 4), the modelling community within WCRP expressed the will to use CMIP to focus not merely on carbon dioxide emissions scenarios, but also on a range of scientific questions. Through an extensive process of consultation across the broad climate community, the simulations comprising CMIP 5 were discussed and prioritised. CMIP 5 included control and historical simulations, climate change scenarios, as well as experiments on regional downscaling, decadal prediction, and a range of 'idealised' experiments to help advance understanding of physical processes. CMIP 6 design was also based on a survey amongst climate scientists (Stouffer et al., 2017). Organised under the auspices of the WCRP to support IPCC reports, CMIP has evolved considerably from a few simulations performed by 18 models in 14 modelling groups for CMIP 1, to thousands of simulations performed by over 100 models in 49 modelling groups for CMIP 6.

The CMIP-standardised dataset allows researchers to align and compare different model simulations and to construct multi-model ensembles of future projections. However, the scientific interpretation of these ensembles is not obvious: an output common to several simulations is not necessarily a guarantee of robustness – it might arise from an error common to all models, and an 'average' result is not necessarily more credible than others. More importantly, different models are not fully independent of each other, since they are tied to predecessor versions or else they exchange ideas and codes with other modelling groups. The spread of model outputs does not therefore systematically explore the uncertainty about future climate change (Knutti et al., 2013). Nevertheless, by making it possible to distinguish the patterns common to all models from those that differ, CMIP has made it possible to advance understandings of the multi-model ensemble outputs that now lie at the heart of the IPCC reports.

CMIP has transformed the way climate scientists work by strengthening coordination, encouraging the standardisation of scientific practices, and considerably widening the user community. This would unlikely have happened – or not have happened as quickly – without the presence, and demand, of the IPCC. The free availability of multi-model output far beyond the modelling teams 'ushered in a new era in climate change research' (Stouffer et al., 2017). But it also created a growing gap between model developers and model users, who still regard GCMs as a 'black box' (Touzé-Peiffer et al., 2020).

14.5 Achievements and Challenges

Today, climate models are rarely called into question in the public sphere, as was still the case as recently as in 2009/10 when climate scepticism was rising in Northern America and Europe (see Chapter 6). Climate models have made it possible for the IPCC to formally attribute global climate change to anthropogenic greenhouse gas emissions. They have shown their ability to reproduce twentieth-century and palaeoclimates, and to produce credible future climate projections, even pre-empting the detection of global warming in climate observations. But now that the IPCC has successfully relied upon climate models to raise awareness of human responsibility for climate change, and pointed to the range of magnitudes of possible future climate change, what is the future role of models in the IPCC?

Two often-cited and growing uses of climate models are for the attribution of extreme climate events to anthropogenic climate change, and for generating climate forecasts at regional or local scales in order to guide necessary adaptations. However, the demand for local forecasts brings into focus the limits of climate modelling. Climate change is more detectable and predictable on large continental scales than on smaller ones: as the spatial scale of climate predictions decreases, uncertainties increase, making it more difficult to distinguish anthropogenic climate change from natural climate variability. Moreover, at local scales, meteorological and social causalities become increasingly intertwined. For example, it can be problematic to attribute to climate change disasters that also arise from socio-political causes, such as social vulnerabilities, inequalities or poor management (Lahsen et al., 2020).

How should models evolve to improve understandings of climate and to better predict future climate? Debates have arisen among modellers. How far should climate models be made ever more complex? Some scholars are considering models that would include ‘human systems’ as an integral part of the Earth system (e.g. Schellnhüber, 1999). Social scientists have criticised this global and systemic vision of modelling the entirety of the planet *and* of human action. Their argument is that such a vision invites a techno-managerial approach to shaping Earth’s future (Lövbrand et al., 2015), obscuring the multiplicity of cultural values, the inequality of social situations, and the importance of power relations in making decisions.

Other climatologists believe that despite incontestable achievements, the pace of progress in climate modelling is too slow, the uncertainties decrease by too little, and systematic errors remain for many years. Some advocate very high-resolution models (Shukla et al., 2009; Voosen, 2020). But this approach, according to others, does not provide the sets of climate simulations necessary to explore climate variability. Some suggest joining forces to build a unique model from scratch, but others stress the importance of keeping open a diversity of modelling approaches – because of the complexity of the climate system and for fear about the hegemony created by international super-models. Others propose replacing all or part of the model with machine-learning algorithms.

There is no consensus among climatologists about whether GCMs will be able to produce regional quality forecasts, whether they will continue to evolve towards greater complexity, towards very high resolution models, or even towards another type of simulation tool – or even what the place of models will be in future IPCC reports. These debates might seem to be reserved for a handful of climate modellers. But the future of climate modelling will determine much of the future knowledge that will be evaluated and synthesised by the IPCC. The future of climate models therefore concerns not just climate modellers, but decision-makers, policy advisors and, indeed, all people on Earth.

Three Key Readings

Edwards, P. (2010). *A Vast Machine. Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press.

This book tells the story of climate science as a ‘global knowledge infrastructure’ and shows how observation networks and climate models have made the global warming problem emerge and grow.

Shackley, S., Risbey, J., Stone, P. and Wynne, B. (1999). Adjusting to policy expectations in climate change modeling: an interdisciplinary study of flux adjustments in coupled

atmosphere-ocean general circulation models. *Climatic Change*, 43: 413–454. http://doi.org/10.1023/A:1005474102591

This article, based on a survey in 15 modelling groups, is an early STS study of climate modelling showing the diversity of the practices of these groups and of their relationship to the political implications of their research.

Touzé-Peiffer, L., Barberousse, A. and Le Treut, H. (2020). The Coupled Model Intercomparison Project: History, uses, and structural effects on climate research. *WIREs Climate Change*, e648. doi.org/10.1002/wcc.648

This article retraces the history of the CMIP, highlighting its close links with the IPCC and its effect on climate research.