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How Climate Models Gain and Exercise Authority

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<A>Introduction

Numerical climate models have become central to the unfolding story of climate change. Climate models underpin the knowledge claims and risk assessments of the Intergovernmental Panel on Climate Change (IPCC), claims and assessments which powerfully shape political narratives of climate change (Manuel-Navarette 2010) and animate new social movements (Jamison 2010). Climate models seem essential for the detection and attribution of anthropogenic climate change, heavily informing iconic expert judgements such as: "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse has concentrations" (IPCC 2007a: 10; emphasis in the original). Climate models are also being deployed to attribute extreme weather events, such as individual heat waves or flooding episodes, to human influences (Pall et al. 2011). And numerical climate models offer novel access to the distant future by simulating the climatic consequences and their impacts of different development pathways being chosen around the world: "Anthropogenic warming could lead to some impacts that are abrupt and irreversible" (IPCC 2007b: 53). By anticipating the future in this way, climate models have become a prosthetic-to-human moral and ethical deliberation about long-term decision-making.

Numerical climate models[1] have therefore acquired significant authority in the contemporary world – if by authority we mean "the power to determine, adjudicate, or otherwise settle issues or disputes".[2] They exercise this power and influence over the academy, over policy debates, and over the human imagination as the following quotations show (emphases added):

> (from scientists) "*Climate models* will … play a … perhaps central role in guiding the trillion dollar decisions that the peoples, governments, and industries of the world will be making to cope with the consequences of changing climate … adaptation strategies require more accurate and reliable predictions of regional weather and climate extreme events than are possible with the current generation of climate models" (World Modelling Summit for Climate Prediction 2008; quoted in Goddard et al. 2009: 343).
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> (from campaigning organisations) "But, with the advancement of global *climate models* to three-dimensional coupled entities, with ever increasing spatial resolutions, it is now known that the impacts of climate change will manifest in more extreme local changes in temperature" (nef 2008: 3).

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[1] In this chapter I use "climate models" as the generic term to describe the whole family of numerical climate models, which includes simple one-dimensional models, intermediate complexity models, general circulation models, and Earth system models.

[2] www.dictionary.reference.com.

(from religious organisations) "The aims of the Church of England's Shrinking the Footprint campaign rely on the accumulated weight of evidence from scientific observation and modelling. The campaign will continue to maintain awareness of … projections from *climate models* of the climate system" (Church of England 2009: 8).

(from public intellectuals) "The relentless logic of the *[climate] models* proves over and over that the poor and vulnerable will be hardest hit by climate change" (Hamilton 2010: 201).

How can it be that climate models are able to exert authority over trillion-dollar decisions, over religious organisations, and over the human imagination of the future? What sort of authority is it that is being exercised? How do climate models gain this authority, and how do they retain it? And in what ways is this authority differently recognized between cultures?

The UK's Royal Society's motto famously asserts "*nullius in verba*" – "on the word of no-one"; i.e. accept nothing on authority. The corollary of such scepticism is carefully to observe, test, and experiment. This challenge to received wisdom was characteristic of the cultural shifts in Europe of the late 17th- and early 18th-century Enlightenment which gave birth to the Royal Society. Yet it is a scepticism that human beings find difficult always to practice. Deference to the elder, the priest, the celebrity, or deference to the claims of science itself is difficult to eradicate. We want to be reassured about the future, to establish some authority which can tame and manage our fears about it.

Although of necessity we accept many things on authority each day, in the case of climate models is this deference warranted? The IPCC Fourth Assessment

Report claimed in 2007: "There is considerable confidence that [climate models] provide credible quantitative estimates of future climate change, particularly at continental and larger scales" (IPCC 2007a: 591). Is there considerable confidence? For whom and for where? And for what purposes is such confidence claimed?

The question, therefore, I wish to address in this chapter is: "How do climate models gain and exercise authority?". There are two interrelated dimensions to the authority of climate models which need examination: the source of climate models' epistemic authority and the source of their social authority. *Epistemic authority* arises primarily from models using mathematical expressions of physical laws to represent reality. And yet climate models remain significant abstractions and simplifications of reality. On the other hand, climate models' *social authority* resides in the interactions between scientific practices, cultural performances, and political interests, interactions which endow models with the status of trustworthy "witnesses" to the truth – or not.

These two dimensions of authority relate in complex and varying ways. Understanding this relationship – and hence understanding the authority exercised in society by climate models – requires critical philosophical, sociological, and anthropological analyses. As Hastrup (Chapter 1, this volume) observes, climate models and modelling "have a social life of their own" and the practices of design, communication, and interpretation of climate model simulations are always socially embedded.

<A>*Epistemic Authority*

The epistemic power of climate models comes from their being rooted in strong physical theory and from their deployment of mathematical expressions of such theory to represent the physical dynamics of oceans, atmosphere, and ice sheets. For example the Navier-Stokes equations describing the motions of fluid substances are central for all advanced numerical weather and climate models.

And yet climate models remain significant abstractions and simplifications of reality. Wherever one looks in the representational structures of climate models, one finds exclusions, approximations, and parameterizations of observable physical processes. Paradoxically perhaps, the greater the number of physical processes that are represented in a climate model, owing to the expanded degrees of freedom the greater are the uncertainties in projections of future climate states made using that model. As a leading American climate modeller has expressed recently when reflecting on this paradox in the context of the next IPCC assessment due in 2013/14: "The spread in initial results is therefore bound to be large and the uncertainties much larger than for the [climate] models in the last IPCC assessment. There are simply more things that can go wrong" (Trenberth 2010: 20–21; see also Knutti 2010). Models such as these with (too) many degrees of freedom may almost be thought of as "nervous models".

These epistemic characteristics of climate models leave us with an unresolved tension. Do climate models provide answers to questions such as "how large will be human influences on the climate system during the next century?", or "do climate models generate proliferating data from which more questions emerge?" (Overpeck et al. 2011)? What exactly is the purpose of climate models: heuristic tools (metaphors even; Ravetz 2003) for understanding climate processes, or truth machines for predicting future climates? Naomi Oreskes and colleagues in their famous 1994 paper on climate model verification argued that "the primary value of [climate] models is heuristic … useful for guiding further study, but not susceptible to proof" (Oreskes et al. 1994: 644). Others may suggest that both functions are valid (see Heymann, Chapter 11, this volume), but if so then the relationship *between* the heuristic and predictive roles of climate models requires us to consider the social life of models.

<A>*Social Authority*

The social authority of climate models emerges from the interactions between scientific principles and practices – those that give rise to their epistemic authority, as we have just seen – and the public visibility and performances of these models in the social sphere. As with Steven Shapin and Simon Schaffer's idea of socially validated knowledge through "public witnessing" of the performance of Boyle's air-pump in the 17th century (Shapin & Schaffer 1985), climate models need to be "seen" to be performing credibly and reliably. They need to be "made" trustworthy – worthy of the trust of the public. To earn their social authority climate models therefore need to inhabit public venues, displaying to all their epistemic claims of offering credible climate predictions.

These forms of "public witnessing" of climate models may include displays of computational power (images of powerful computers with captions such as "The supercomputer Tupã aims to take the world by storm"; Tollefson 2010), colour-rich animated displays of simulated virtual climates (Schneider 2012), and public endorsements from powerful (political) or trusted (celebrity) actors, as in some of the quotes listed in the introduction. Many of these forms come together in the authorisation of climate models through the cultural idiom of computer gaming. For example, the computer game *Fate of the World* released in 2010 by the Red Redemption team (http://fateoftheworld.net/) defers to climate modelling in this way – as the source of "realistic data" through which "opportunities for learning about climate change available for players are huge" and which "can have a positive impact, especially on younger players". And as an expert witness to the credibility of climate models the IPCC itself has been particularly important.

Such varied forms of public witnessing endow climate models with social authority. But note – and I shall return to this later – the particular forms and statuses of social authority acquired by climate models are culturally conditioned and therefore can vary, sometimes very substantially, both within and between societies.

<A>*Climate Model Reliability*

Keeping in mind these opening considerations about the relative roles of epistemic and social authority of climate models, I will structure the following exploration in terms of the specific question: "Are climate models reliable?" As later explained, I do not mean "reliable" in the narrow sense of whether or not models offer accurate representations of reality, but rather the broader question about the "reliability" of a climate model for particular purposes and within particular cultures. To assist in this investigation, I draw upon the work of Arthur Petersen in the Netherlands by adding two further dimensions of "reliability" to Petersen's original two-fold typology (Petersen 2006). I suggest here a four-fold typology of climate model reliability: coding precision (Reliability 0; henceforth R_0); statistical accuracy (Petersen's R_1); methodological quality (Petersen's R_2); and social credibility (R_3). We look briefly at each of these in turn.

<B>*R_0 Coding Precision: Is Mathematical Representation of Physical Theory Converted into Stable Computer Code?*

This is perhaps the narrowest and most technical definition of model reliability. How well are the physical-mathematical relationships in a conceptual climate model converted into computational algorithms and thence executable computer code? Imprecision (through the choice of numerical solutions to differential equations) and errors (in often millions of line of computer code) are inevitable in this process, but is the resulting code stable? And is it portable across computational platforms and useable by others outside the original design group?

R_0 is usually assessed internally by climate modelling teams, but there may be occasions when this element of model reliability becomes contentious and demands are made to “open up” the model. Indeed, in recent years the “open-source movement” (e.g. Bradley 2005) has spread into climate modelling with organisations like Climate Code Foundation and Clear Climate Code seeking to bring greater professional scrutiny and quality control to bear on climate model codes. Pipitone and Easterbrook (2012) analyzed software from several leading climate models claiming that “in order to trust a climate model one must trust that the software it is built from is built correctly” (p.348). Their conclusion was that climate models have “very low defect densities” relative to other similar-sized open-source projects. Even so, this commitment to open-sourcing climate model code is a time-intensive task and modellers themselves may be reluctant to commit to it even in the cause of public trustworthiness. As NASA climate modeller Gavin Schmidt remarks: “Of all of the things that I can do that are important, is allowing reproducibility of my code on somebody else's computer important? No, that's not important” (reported in Kleiner 2011: 12).

Although calls for greater accountability and transparency in climate modelling are likely only to increase in the future, there may be both practical and theoretical limits as to how far the millions of lines of climate model code can be perfected. Which leads us next to consider reliability R_1.

<B>*R_1 Statistical Accuracy (or "Realism"): Do Model-Simulated Climates Bear a Resemblance with Observed Climates?*

It was this aspect of climate model reliability which first brought me into direct contact with climate models. In 1988 I arrived at the University of East Anglia, hired to work on a research contract concerned with model validation funded by the UK Department of Environment (DoE). The UK DoE desired an independent analysis of how well the climate model which they funded – at the UK Met Office, later the Hadley Centre – simulated observed and palaeo-climates. My earliest work in this area was published in Hulme (1991).

Evaluating how well models simulate reality sounds relatively straightforward, but this is far from the case. There are both philosophical and practical (technical) problems involved with this task. These have been well rehearsed so I will not dwell on them here, but in summary the following points need emphasis. As pointed out by Oreskes et al. (1994), model verification is only possible in closed systems. In contrast, models of complex natural systems such as climate can never be fully verified because such models always require input parameters that are incompletely known. A second philosophical problem with climate model verification is that of underdetermination or equi-finality: differently designed and configured models may yield the same result and so model results are always underdetermined by the available data.

From a practical perspective the problems of evaluating R_1 are greater still (Lane & Richards 2001; Shukla et al. 2006; Stainforth et al. 2007; Gleckler et al. 2008). The observed data against which model simulations are verified are never fully independent of modelling assumptions: they are "model observed" data rather than "purely observed" data. Then there are the large number of performance indices against which a model can be evaluated. How do we judge which of these are most important for establishing the reliability of a model? And, thirdly, how much similarity between a model simulation and observed reality is deemed enough to establish reliability? Different levels of statistical confidence imply different levels of trust or belief in the veracity of the model (Valdes 2011).

There is the further difficulty in that model predictions of long-term (multi-decadal) climate change are impossible to verify – in the direct sense that would be used, for example, to verify daily weather forecasts. Only with the benefit of 20 or more years of observations after the prediction was made could such verification be possible. One rare example of climate model multi-decadal forecast verification is of the predictions made in 1988 by the NASA GISS climate model led by Jim Hansen. Hargreaves (2010) contrasts the 20-year predicted global warming trend (0.26°C/decade) from this climate model with that observed (0.18°C/decade), but concludes that the model prediction demonstrated substantial statistical "skill"; i.e. the model performed better than chance. Yet this type of climate model verification is rare and very limited in scope. And as argued by Oreskes et al. (1994), the underlying climate model (as opposed to the model prediction) cannot be validated by such an exercise.

<B>*R_2 Methodological Quality: Are Climate Models Well Constructed?*

If R_1 is focused on the reliability of climate model *outputs*, then R_2 focuses on the quality of what we might call climate model *inputs*, namely: model structure, boundary conditions, simulation design, levels of expertise, external collaborations, and so on. Petersen and Smith (2010: 5) describe this aspect of climate model reliability thus: "That which derives from the methodological quality of the different elements in simulation practice, given the purpose of the model".

There are a variety of ways of assessing the reliability of climate models in these terms. We might assess model design and structure: is it simple, elegant, or overly complex? We might ask whether or not the modelling team followed appropriate professional standards in software design and documentation (Lane & Richards 2001). Or we might consider the levels and ranges of expertise, which have contributed to climate model design. For example, should physical oceanographers rather than marine biologists design the ocean biogeochemistry module of a climate model? This was the essence of criticism levelled at the Hadley Centre modelling team by a UK House of Commons 1999 enquiry into scientific advice on climate change: "While the Hadley Centre is very expert in climate modelling and in the physics and mathematics of climate change, *it lacks expertise in other disciplines*, notably the biological sciences … We strongly suggest that it might benefit from more in-house staff with expertise outside meteorology, including the biological sciences" (House of Commons 1999: para 12; emphasis added).

Underlying much of this R_2 evaluation of climate models is the thorny question about whether or not different models do – or should – converge on the same simulation or prediction results. Climate models are rarely independent of each other (no one yet knows how to establish "degrees of independence" of climate models; Pirtle et al. 2010) and prediction convergence may simply imply that all models are equally wrong. Is prediction convergence across the population of climate models therefore a sign of reliable physical theory and well-designed models? Or is it merely a sign of a high level of model interdependence: the same experts, using the same algorithms, calibrated against the same data? Should we trust models more or less when they yield similar results – what does it mean when climate models agree?

The IPCC has adopted an approach which uses multi-model ensembles to quantify the range of uncertainty in climate model predictions. Each model is treated as an equally valid representation of reality and hence given equal weight in the ensemble-mean. One model, one vote. But is such a “democracy of models” the right form of representative politics when seeking the truth? Climate modeller Reto Knutti has warned against complacency here: “There is a real danger of model convergence as a result of tuning, consensus on metrics and peer pressure, rather than improved understanding and models … The benefit of a more narrow projection must be compared to the potential damage of overconfident projections and wrong adaptation decisions resulting from it” (Knutti 2010: 401). Paying careful attention to the methodological quality of the “inputs” into climate models and model simulations – what is meant here by R_3 – is therefore one way of warding off such unwarranted overconfidence.

<B>*R_3 Social Credibility: Are Climate Models Socially Authorised to Speak?*

Considerations of R_2 are still largely contained to practices internal to climate modellers and their scientific networks (although external public scrutiny through regulated modelling and professional standards may begin to enter). But does coding precision in climate models (R_0) combined with “adequate” statistical accuracy in their simulations (R_1) and suitable methodological quality in their design (R_2) automatically generate trustworthy models? My argument is “no, it doesn’t” and so a fourth aspect of climate model reliability – R_3 – requires careful scrutiny, namely how climate models exist and operate as social objects.

To scrutinize climate models according to this criterion requires examination of the networks that allow models to enter, endure, and travel in society. These include the following networks with their attendant investigations:

- epistemic networks (as we have seen above): studying which experts are enlisted in model design and the (often implicit) hierarchies of expertise involved;
- financial networks: the majority of (large) climate models are funded by national government agencies and the politics of model-funding are important to unveil;
- political networks: climate change mobilizes a wide array of interests and actors and it is important to understand how climate models are deployed in the politics of climate change knowledge;
- discursive networks: language and rhetoric are used powerfully in the communication of climate model outputs and careful attention should be paid to the representations of certainty, uncertainty, and ignorance in such communications;
- performative networks: climate models claim to capture and simulate reality in virtual form and so making such realities visible requires sophisticated and subtle visualizations through animations, colours, virtual globes – these require critical scrutiny.

Through attaching themselves to and exploiting such networks climate models compete for and acquire social authority – the right to "determine, adjudicate, or otherwise settle issues or disputes". To illustrate some of these aspects of R_3, I draw upon the work of Martin Mahony and his examination of the UK Met Office's Hadley Centre's PRECIS model (Mahony & Hulme 2012).[3] PRECIS is a regional climate model of high (25 kilometres) spatial and temporal (daily) resolution, which over the last decade has been made available to over 100 countries worldwide. It is a

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[3] PRECIS stands for: Providing Regional Climates for Impacts Studies.

modelling system, which has been designed to assist adaptation and development planners in the “global South”. Through investigating how this one model has managed such extensive geographical reach we can see how these different enabling networks work to establish its social authority.

PRECIS carries with it the pedigree of the Hadley Centre’s Earth system modelling enterprise. This pedigree of being bred from one of the world’s leading climate modelling centres is jealously guarded. Although PRECIS has been distributed to over 100 countries, it is done so on certain conditions that tie the model back to its epistemic parentage. PRECIS also extends its reach across the world through the financial backing of the British Government. It has received either direct or implicit support in its developmental trajectory from three national government departments: the Ministry of Defence, the Department for Energy and Climate Change, and the Department for International Development.

PRECIS has been able to exploit international political and diplomatic climate change networks and thereby further extend its reach and authority. As one of the PRECIS development team remarked, “’It was also useful for us to have the UNDP [United Nations Development Programme] seal of approval on it’ to lend credence to the chain of translation” (Mahony & Hulme 2012: 201). Working through such overtly political networks grants additional authority to PRECIS and so enables users to justify political action on the basis of PRECIS’ outputs. For example, this PRECIS user from the Caribbean reflected, “We were able to convince the international audience that even though they’re talking about 2[°C], 2 would be extremely detrimental to us. So … outputs from models like PRECIS help us in terms of our convincing of policy makers that they should take a stand” (Martin Mahony personal communication, September 2010).

The authority of PRECIS is also illustrated through its ability to engage with the discursive networks of climate change and development. In particular, its promotional material has been able to deploy the language of social vulnerability combined with scientific prediction thereby making the model "useful". In so doing PRECIS' authority is lent in support of this particular framing of climate change adaptation. As Mahony and Hulme (2012: 208) conclude, PRECIS facilitates interaction between scientific and political worlds

> in support of a particular political sagacity. This is achieved through the … deployment of normative discourses of vulnerability and scientific realism, the consequence being a community pursuing [climate change] knowledge which possesses high spatial resolution and precision. This pursuit is facilitated by the rendering of planned adaptation as captive to, or an ancillary of, the ability to predict future climatic changes on the scales that most interest decision-makers.

Finally in my list of five enabling networks of authorisation, the epistemic authority of PRECIS is displayed performatively by showing visually its "realism" in comparison with other lower resolution models. Credibility for PRECIS is therefore established visually, as much as it is established statistically (R_1), through frequent use of coloured graphics. These emphasize the difference made by high resolutions to the representation of familiar geographic forms, whether they be coastlines or familiar meteorological features such as tropical cyclones. As Mahony and Hulme (2012: 202) explain:

> A comparison is presented of the representation of the Philippines at various spatial resolutions (400, 50, and 25km). As the resolution of the model increases, the shape of the coastlines becomes more detailed, more isles appear on the map, and the overall picture becomes one of topographical clarity with the islands recognisable to anyone familiar with the geography of the western Pacific.

This performative demonstration of PRECIS' epistemic authority suggests that the model can tell us something about the *real* world and the *real* atmosphere and is not merely a heuristic tool.

As PRECIS has moved around the world in recent years, the model has gained social authority by imposing itself on distant cultures through a process Mahony and Hulme (2012) describe as "epistemic hegemony". The PRECIS model is a good example of the co-production of scientific knowledge and social order at work (Jasanoff 2004), in this case mediated by a climate model. This extended example illustrates the many different functions this "mobile model" has secured through it global passage, functions that go well beyond Oreskes' notion of a climate model as a heuristic or Ravetz' suggestion of climate model as metaphor. PRECIS has both gained and exercised authority in society.

Further insight into the social authorisation of climate models comes from considering how climate models have been deployed in two different science-policy cultures: the UK and the Netherlands. In recent years both countries have created sets of national climate scenarios of the future, commissioned by their respective central governments. Both countries have strong scientific traditions and have valorised evidence-based policy. And yet in the design of these respective climate scenarios climate models have been granted different degrees of authority over the (climatic) future.

In the UK, the national scenarios developed in 2009 (Murphy et al. 2009) drew almost exclusively on climate model simulations and in particular on one model hierarchy from one modelling centre (the Hadley Centre). This was justified through claims that it offered the world's most advanced climate modelling system. Various sophisticated statistical techniques were used to convert model output into probabilities of future weather outcomes at very fine temporal (hours) and spatial (5 kilometres) scales. In the Netherlands, however, the four national climate scenarios were developed using a greater diversity of methods and techniques than in the UK (KNMI 2006). Although climate models and their simulations remained important, the exercise sampled a wide spread of model hierarchies and combined model simulations with historical evidence, local meteorological reasoning, and expert judgement. Lesser authority was granted to a single climate modelling system and its simulations than in the UK case.

It is enough for my purpose here to show that R_3 can vary radically across different cultures and decision-making practices, even if climate models are adjudicated to possess similar degrees of reliability across the other three levels of assessment. In this example of climate scenario construction, climate models are granted very different authorisations to create and guide descriptions of future climates, which may then be used to inform public (or private) decision-making. There is a note of caution here for the way in which the IPCC conducts its work and establishes its universal knowledge claims based on models. Its authoritative deployment of climate models with their representation of putative future climates becomes potentially dangerous if in so doing the IPCC erases, or is oblivious to, differences between cultures in the social authority that is granted to these climate models (Hulme 2010).

<A>*Conclusion*

This chapter has explored how climate models gain and exercise authority in society. There is no doubt that climate models offer a powerful way – the single most powerful way – for scientists to organize their knowledge about the physical Earth system, to understand the material interconnections between different parts of that system, and to help identify key sensitivities within it. To construct, maintain, and use a model implies at least a minimal level of understanding of physical causation in the complex Earth system, and an ability to re-create features of that reality in a simulation machine. Climate model simulations must have some correlate in the observable physical world. If they do not, then as much effort must be invested in understanding the behaviour of the climate model as in understanding the physical Earth system. It is the model that is deficient in some respect, not reality (Lahsen 2005). Climate modelling has in many ways therefore become a behavioural science: a science which studies the behaviour of climate models.

Whether the public, and the politicians they elect, should trust climate models when they are used to prognosticate about the far future – and hence whether they should defer to decision-making calling upon the authority of models – requires an additional set of questions to be answered. It is not enough for climate modellers to speak about the stability of their code (R_0), or about the fidelity of their simulations (R_1), or about the quality of the underlying model structures and design processes (R_2). Even less is it enough to be told that all climate models (broadly) agree. To gain authority within certain forms of democratic life it is important that the networks and practices that support and authorise the social life of climate models are subject to critical scrutiny. As with other authoritative voices and institutions in society (Brown 2009), climate models and their networks must be held accountable to broader sets of public norms and standards.

These norms are socially constructed and they will therefore vary between cultures and nations. It is insufficient to assert that climate models possess universal and uniform authority simply on the basis of their epistemic power. Such claims are common in the world of climate modelling – just as they are often also subliminal, as in this recent example commenting on new developments in Brazil's modelling community: "The [new] supercomputer could help to earn Brazil a place in the small club of nations that contributes global climate-modelling expertise to the IPCC" (Tollefson 2010: 20). The implication here is that a new generation of climate models operated through a new powerful supercomputer will not just enhance Brazil's scientific modelling capacity, but will also enhance Brazil's political authority in the "club of nations".

Beyond such superficial claims, it is understanding the social credibility of climate models – what I have termed here R_3 – that is critical. For climate models to gain the status of "trustworthy witnesses" it is necessary but insufficient that they be evaluated against the reliability criteria R_0, R_1, and R_2. Rather, R_3 has to be evaluated, case-by-case, keeping in mind the distinct "civic epistemologies" of different political cultures (Jasanoff 2005). And ultimately it is the ways in which the claims of epistemic authority are socially validated that yield greatest insight into how climate models gain and exercise authority in society.

Climate models "take on a life of their own once they have been unleashed into society and politics" (Hastrup, Chapter 1, this volume, p. XX). They need to be studied not merely as tools of scientific enquiry, but as powerful social objects. Such study cannot be left to climate modellers. We need the insights and tools of philosophy, sociology, and anthropology to understand how climate models gain authority and how this authority is exercised differently around the world.

<A>Acknowledgments

Earlier versions of this chapter were presented at the CRASSH Conference "Challenging Models in the Face of Uncertainty" at the University of Cambridge (September 2010), at the University of Colorado, Boulder (November 2010), and at the *Waterworlds* workshop "Anticipating Nature" at the University of Copenhagen (January 2011). Discussion and questions raised by participants at each of these events is gratefully acknowledged, as is the close reading of this chapter by Kirsten Hastrup and Martin Skrydstrup. The ESF exploratory workshop "Epistemic Shifts in Computer-Based Environmental Sciences" held at Aarhus University (June 2010) introduced me to the "model reliability typology" of Arthur Petersen.

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