6 Hélène Guillemot: How to develop climate models? The “gamble” of improving climate model parameterizations

6.1 Introduction

How should predictions of the future climate be improved, and confidence in those predictions increased? What is the way forward for computer models, key instruments of the climate sciences and the only accepted tools for predicting climate changes? The principal driving force behind climate modeling seems to be the exponential growth of computing power, allowing models to include ever greater numbers of physical, chemical and biological components, with growing spatial resolution, in order to provide projections of climate change at a regional scale (see Mahony, this volume). However, this trend is not hegemonic, and in the climate sciences community, the debate about strategies for model development rages on.

Indeed, despite major progress in computing and observation, the precision and reliability of climate change predictions have changed little over the last decade. Climatologists have long known that the flaws and uncertainties of simulations are mainly attributable to their representations of sub-grid scale physical processes such as clouds and convection, known as parameterizations. These parameterizations thus lie at the heart of animated debate: are they in a “deadlock” (Randall et al., 2003)? Why have developments in modeling been failing to lead to corresponding improvements in prediction?

In this chapter, I will rely on the development of a new parameterization—the representation of convection and clouds—of the climate model of the Laboratoire de Météorologie Dynamique (LMD) of the CNRS, in Paris, to shed light on the practices, choices and points of view of LMD researchers and other modeling groups with regard to model development. The first section exposes the discussions on parameterizations versus other strategies for model development; the second section looks at the design, construction and validation of the new parameterization of the climate model of the LMD; finally, in the third section we will see that these different approaches involve varied epistemic conceptions of models, and of their roles, uses, and limits, grounded in different practices and institutions. In all, this chapter demonstrates how the existence of different ‘cultures of prediction’ fundamentally shapes the courses of climate model development.

6.2 Debates on the evolution of climate modeling

For some years, there has been animated debate on the development of models: the World Climate Research Program (WCRP) has organized numerous workshops and conferences on this topic; reports and articles have been published by researchers and groups seeking to advance their own visions of the direction that climate modeling should take (Jakob, 2010; Jakob et al., 2010; Shukla et al., 2009; Knutti, 2010; Randall et al., 2003; Bony et al., 2011; Held, 2005). To grasp what is at stake, a look at the structure of climate models and the role of parameterizations is needed.

6.2.1 The dual structure of the Global Circulation Models

Atmospheric models – be they climate models or numerical weather prediction models – simulate planetary-scale atmospheric flow as represented in a three-dimensional grid; this is why they have been called Global Circulation Models (GCM). For each grid cell and at each time step, the computer calculates the value of the variables characterizing the mean state of the atmosphere within the cell (temperature, wind, humidity…) from their values at the previous time step, by calculating the algorithms that constitute the model. Atmospheric models are organized into two parts: a "dynamic core," which describes the movements of air masses at the grid scale using algorithms which discretize the laws of fluid dynamics (Navier-Stokes equations); and a so-called "physics" part, which deals with the physical processes that influence weather or climate occurring at various scales below the grid scale (the grid size in a climate model is about a hundred kilometers). These sub-grid scale processes are represented by "parameterizations" describing their statistical impact on large-scale variables.[1]

The dynamic core of the model represents the system of the global atmosphere, which obeys fundamental laws (conservation of energy, mass, water...) on a large scale. With parameterizations, however, additional theories and formalisms are incorporated into climate models (Galison, 1996). Thus climate (or weather) models rest on a decoupling of explicitly calculated large-scale dynamic and small-scale phenomena whose effects must be represented statistically. GCMs are deeply structured by this duality, which has subsisted since their inception, although they have changed considerably in size and complexity over time.

Parameterizations are extremely diverse: some are veritable physical models within the model, with their own internal variables and their own equations, others are more empirical. From the very beginning of weather and climate modeling, atmospheric physicists have identified essential subscale processes responsible for the exchange of energy, momentum and/or water between the atmosphere and the earth surface: radiative transfer, small-scale turbulence transporting energy in the boundary layer (the layer of air in the immediate vicinity of the surface), convection on a larger scale, clouds, precipitation, etc. These processes were taken into account in the first models through simple parameterizations, which have since been greatly refined. Broadly speaking, these improvements consist in replacing fixed or "tuned" parameters with sub-models of physical processes (which themselves include empirical or tuned parameters, at a lower level). For example, the first climate models represented convection as a large-scale adjustment, transporting energy and humidity toward the upper atmospheric layers and eliminating water beyond a saturation threshold, through condensation and precipitation. In later models, convection has been described on more physical grounds, and its interactions with other processes represented.

Over the course of their half-century of history, climate models have been developed both through improvements in these main parameterizations, and through the integration of new components to include more milieus and phenomena: the ocean, sea ice, vegetation, ecosystems, atmospheric chemistry, carbon cycle, marine biogeochemistry etc. – thus becoming "Earth System Models." During the 1990s and 2000s, core physical parameterizations were somewhat neglected in favour of the complexification of models and coupling with other components of the earth system (Dahan, 2010). Some climate researchers have criticized this "overemphasis on new components that increase complexity (…) often without adressing existing big or longstanding problems" (Jakob et al., 2010: 3-4). But in the past several years there has been a growing awareness of the need to improve the core of the models.

6.2.2 Persistent biases and need for better core parameterizations

Despite substantial progress in many domains, the range of uncertainty on climate sensitivity[2] has not decreased since the first IPCC reports (1.5 to 4.5 degrees), and there is relative stagnation with regard to main flaws in climate models: to take just one example, little is known about how to simulate precipitation in tropical regions and how it would change in a warmer climate. Climatologists know that many of these recurring flaws are due to the poor representation of sub-grid-scale processes, of clouds and convection in particular. As these processes are represented differently depending on the model, the parameterizations of clouds and convection constitute the main sources of uncertainty for projections of the future climate.

Yet developments in climate science seem to provide opportunities for the improvement of core physical parameterizations. Nowadays they have been recognized as critical for the quality of simulations and hence for research on the impacts of climate change: all components of the climate depend on the representations of main processes (no good representation of vegetation dynamics or carbon cycle without a good distribution of precipitation). The improvement of parameterization is also favored by the current availability of an unprecedented range of observations – ground-based, space-borne and in situ campaigns – to the point that some consider that we live in a "golden age" of observations.

Moreover, for 20 years international research programs have been dedicated to improving GCM parameterizations using knowledge acquired through detailed modeling of clouds and convection. High resolution numerical modeling saw considerable growth in the 1980s; these limited area models explicitly calculate the vertical convection movements within the atmosphere, which in GCMs, in contrast, are parameterized.[3] Two types of small scale models are distinguished: Cloud Resolving Models (CRM; grid cells on the order of a kilometer, domain of 100 to 1000 km) and Large Eddy Simulations (LES: grid cells 10 to 100 m in size, domain of 10 to 200 km). LES and CRM models have made it possible to study and simulate all categories of clouds in many types of climate, as well as their collective organization (squall lines, storms...). The development of high-resolution models benefited from large-scale, open-air experiments organized over the last 40 years, involving several international teams and instruments transported by boat, airplane, balloon and satellite, in order to observe a particular atmospheric process (storms in the Atlantic, the West African monsoon, etc.). Beginning in the 1990s, international programs like EUROCS (European Project On Cloud Systems) and GCSS (GEWEX Cloud System Study)[4] have used these field campaigns to help improve cloud parameterizations, seeking to foster collaboration between the global model community and the process community: "Observations from field programmes will be used to develop and validate the cloud-resolving models, which in turn will be used as test-beds to develop the parameterizations for the large-scale models" (GCSS Team, 1993: 387).

However, although these observations and research programs have indeed improved the understanding of processes, they have more rarely led to major revisions in the parameterizations of models. Scientists involved in that domain advance several reasons for this limited improvement. The considerable effort and time required to conceive a new parameterization (as we will see in next section) does not encourage reopening long-established parameterizations to revision. Some researchers invoke the small number of "developers" as compared to the number of "users," and also the lack of incentives: despite established discourse and programs, the issue of climate change draws research toward regional predictions and impacts more than toward the development of parameterizations[5]. Moreover, this type of activity is reputed to be academically unrewarding: it leads to fewer publications than numerical experiments or simulations, is less valued than opening up new domains – and fits less well with current research funding criteria. As a LMD researcher (L1)[6] explained:

> It's difficult to justify working on old questions. If you don't get the results you need, you have to change topics […] When a problem is new, the system is poorly constrained, you get strong answers; so that gives you papers that are easier to write... (L1, pers. comm., July 2012)

These model developers thus tend to consider themselves a minority, facing the dominant trends in modeling which promote other scientific practices.

6.2.3 The gap between processes and climate

Climate model developers express a disconnection between process studies on the small scale and climate model assessment on the large scale. This young researcher (L2), for instance, senses a lack of communication and of activity between these communities:

> I went to a GCSS conference in Boulder on process studies, fascinating. I asked: where do we talk about the impact that parameterizations have in models, at a large scale and in the long term, on the climate, and about why the models aren't improving? The answer was: it will be talked about in the workshop on systematic model errors in Exeter. I went there. They were looking at what the climate biases were, but this still wasn't the place where we would talk about the question of where these biases come from... But it's not an easy question, we don't know how to do that. You get the impression that there's a lack of activity between these two communities. (L2, pers. comm, December 2013)

Some researchers insist on the need to strengthen links and coordination between the process and climate areas. But the problem is deeper and touches on a fundamental characteristic of climate modeling: the difficulty of attributing the characteristics of simulations to components of the model, because of the multitude of processes and interactions at many scales. This problem is nicely summarized in a WCRP white paper: "model development is hindered by a lack of understanding of how a poor representation of cloud scale processes and cloud scale dynamics contribute to model biases in the large scale circulation features and influence future projections." [7] This "gap between processes and large-scale climate" (in the climatologist's parlance) has been characterized by philosophers as a consequence of the "epistemic opacity" of computer simulation (Humphreys, 2004: 147) or their "confirmation holism" (Lenhard and Winsberg, 2010: 254).

As an instance of this epistemic opacity, even when a new parameterization successfully reproduces an aspect of the current climate, there is no guarantee that the same will be true for the future climate, because the influence of the numerous physical processes may vary in unknown ways over different timescales. That is why, according to certain modelers, improving parameterizations is a "gamble".

6.2.4 Superparameterization and super-models

Given the difficulty of this problem, certain climatologists prefer not to take the gamble and advocate other paths for the development of models. In an article entitled "Breaking the cloud parameterization deadlock," four renowned specialists in cloud physics, considering the considerable amount of complex knowledge on cloud processes and their poor representation in climate models, claim that it is impossible "to parameterize all of this complexity with quantitative accuracy" (Randall et al., 2003: 1551). As "our rate of progress is unacceptably slow" they propose a "new and different strategy" called "super-parameterization," a sort of hybrid between a parameterization and an explicit calculation that consists in replacing the cloud parameterization in each grid cell with a high-resolution two-dimensional CRM-type model (Gramelsberger, 2010). Another strategy was advanced at the World Modelling Summit for Climate Prediction in 2008, and taken up in a "declaration" entitled *Revolution in Climate Prediction is Both Necessary and Possible* (Shukla et al., 2009). This text recommends the launch of a "World Climate Prediction Project" equipped with computers at least a thousand times more powerful than those currently available, in order to develop models at kilometre resolution, capable of explicitly calculating convection and even boundary layer eddies – in other words, extending LES-type detailed models to the entire planet. These super-models, including numerous biogeochemical processes, could provide "operational climate prediction at all time scales, especially at decadal to multidecadal lead times” – what is called “seamless prediction,” merging weather forecasting and climate prediction.

This colossal project provoked rather heated debate in the climate modeling community. Several types of objections have been raised: these models will not be available for several decades; even high-resolution models contain parameterizations, at smaller scales. And if the idea of seamless prediction is seen as interesting, since there is no scientifically relevant boundary between modeling weather and climate, some climate scientists “remain skeptical about the overall benefit of the ‘one size fits all’ model” (Knutti, 2010: 401), because the objectives and ways of working with weather or climate models are different. Another sensitive topic is the risk of a hegemony of international super-models, favoring certain objectives and strategies. The stakes in this *End of model democracy* (Knutti, 2010: 395) are both political and scientific, involving the diversity of approaches, the autonomy of scientific decision-making and the quality of forecasts.[8] Finally, very high-resolution models are not guaranteed to produce good climate simulations: there are discussions on the appropriate temporal and spatial scales for these models.

6.3 The overhaul of a parameterization at the heart of the model

The researchers of the LMD are among those who took the gamble on parameterization. For more than a decade, a few scientists have developed a new parameterization that was implemented in the LMD atmospheric model in 2011.[9] This new version of the model was ready in time to participate (alongside the old version) in the fifth phase of the Coupled Model Intercomparison Project (CMIP5), and thus to be included in the latest report of the IPCC (Intergovernmental Panel on Climate Change).[10]

6.3.1 Representing surface turbulence, tropical storms and fair-weather cumulus

Rather than a single new parameterization, it is a new set of parameterizations that has been developed and recently implemented in the LMD model. The representations of several atmospheric phenomena are now combined: turbulence in the boundary layer (up to an altitude of 10 to 100 m), high-altitude convection with the associated enormous cumulonimbus clouds (so-called “deep convection” – 10 to 20 km), and also an intermediate-scale phenomenon that was not described in previous models: convective movements in the boundary layer (1 to 3 km in altitude), called “thermal plumes,” which give rise to the small fair-weather cumulus clouds.

The representation of deep convection, in particular, has been modified profoundly. The decision to change this parameterization was motivated by a recurring flaw in the LMD model (and in most GCMs): the precipitation time lag in the tropics. In the models, the rains began at noon, whereas in the real world they tend to fall in the late afternoon – a serious bias, which revealed a poor representation of the phenomenon and which had serious consequences for the energy balance in the tropics. The LMD researcher who works on tropical convection (L3) came to an understanding of the origin of this flaw in 2000, in a discussion with a researcher from Météo-France (the French center for weather forecasting) who was a specialist in the study of clouds at a small scale. The time lag is due to cloud-internal phenomena, which had already been observed and studied by climatologists, but not yet taken into account in global models. It took more than ten years for L3 to achieve the representation of these phenomena in a parameterization (which includes processes named “cold pools” and “density currents,” which we will not describe here (Hourdin et al., 2013: 2193).

The new parameterization is the product of a partly individual and partly collaborative work. The first task is conceptualization: parameterizations do not represent all processes, but only those that scientists consider to play an important role (in our case, thermal plumes and cold pools, for example). Here the work consists in designing an idealized representation of the phenomenology of the processes and formulating these mechanisms as equations. Interactions between different processes must be represented as well, and the parameterization must be linked to the large-scale dynamics. The new parameterization of the LMD model represents “a radical change,” according to of one of its creators (L4), because it is based on detailed studies of the actual physical processes: “this coupling between cold pools […] and convection […] allows for the first time to get an autonomous life cycle of convection, not directly driven by the large scale conditions” (Hourdin et al., 2013: 2198).

6.3.2 Collaborations between large- and small-scale modeling

Developing the new physics involved several researchers at the LMD, and gave rise to several PhD theses, but also relied extensively on a collaboration with the scientists at Météo-France's research center who study cloud processes at the small and medium scale by developing and using high-resolution atmospheric models. This collaboration is part of the worldwide dynamic mentioned above, aiming to help in developing parameterization in large scale models by using field campaigns and high-resolution models within the framework of international programs like EUROCS or GCSS.

However, moving from local case studies to a parameterization that is valid on the global scale raises fundamental difficulties. L3 recounted that he had been greatly impressed by the presentation of a high-resolution simulation at a conference in 2008. The speaker showed an animated simulation of convection and tropical storms over 24 hours within a 200-km-wide "box" at a resolution of 100 m.

> The room was silent, everyone was in awe. You could see lots of little density currents meeting each other, interlocking over the continents, in squall lines, fusing, colliding and teeming over the ocean...The conclusion of the speaker as to the possibility of representing parametrically this high resolution simulation was : "It's not manageable"! (L3, pers. comm., August 2012)

Yet L3 tried to take up the challenge of moving from a small-scale, single-day simulation to a large-scale vision. As he explained :

> A parameterization has to be valid for the whole world: we start from the principle that all the storms in the world have density currents. You have to fit an average vision onto the explicit simulations, describe populations of cold pools and density currents statistically. (L3, pers. comm., August 2012)

High-resolution models are used in conceptualizing a parameterization, but also in validating it (Guillemot, 2010), following a methodology that is now well established. The modelers select case studies representative of different aspects of the phenomenon to be parameterized (convection above the ocean, squall lines etc.). For each case study, they perform a simulation with a Cloud Resolving Model at a resolution of 10 km. This high-resolution simulation is initialized and validated by field measurements, and then used as a reference to test the parameterization. To do this, the parameterization is incorporated into a one-dimensional version of the GCM (known as a "single-column model"), which consists of a single horizontal grid cell with all of the vertical layers above it. The exchanges with the exterior provided as "forcing" (heat, humidity) are the same for the single-column model and for the high-resolution model. The simulation drawn from the parameterization can thus be compared to the high-resolution simulation.

As a single-column model is much less computationally intensive than a GCM, while containing its entire physics, it makes it possible to test the parameterization on several case studies, since "to be qualified for 3D climate modeling, a parameterization must be valid both over ocean and continents, from the poles to the equator, on deserts or wetlands" (Hourdin et al., 2013: 2200). Then the parameterization is evaluated using the whole model.

6.3.3 A new parameterization creates disruptions

The final step is the implementation of the new parameterization in the model; it is also one of the most difficult. Indeed, parameterizations developed through process studies have often initially produced poor climate simulations. This apparent paradox is explained by "compensating errors": even if the previous parameterization was inferior to the new one, the model may have been tuned so that its flaws were compensated for by errors in other parameterizations of the model, producing the semblance of a correct climate. Modifying a parameter alters this balance by bringing new feedback effects into play. Thus, as a Météo-France climatologist explained, parameterizations "develop collective behaviours" which contribute to making the model "the expertise of a group." It is therefore essential that the different parameterizations of a model be coherent, with sectioning and process representations that are well harmonized. This is why, after the design work, the development of a new parameterization requires a long phase of adjustment and tuning.

What change in climate simulations did the new parameterization of the LMD model ultimately produce? What are the differences with respect to the old parameterization? The changes are substantial, which is not surprising since the processes represented affect all aspects of the climate and have an influence on large-scale circulation. Improvements were observed, but there was also deterioration in some points. The new parameterization clearly improved the aspects on which efforts had been focused, in particular the representation of boundary layer clouds and the variability of precipitation; and there is no longer a lag in the cycle of tropical precipitation. However, the new version of the model presents the flaws which are common to most coupled ocean-atmosphere models, and in some cases even amplifies these biases (shifted rainy areas, for example)

An interesting result is that the new and old parameterizations lead to markedly different sensitivities to increasing CO2. While the standard version of the LMD model has a high sensitivity (relative to the mean of coupled GCMs), with the new physics the sensitivity is among the lowest. This difference needs to be interpreted in detail, but it doesn't come as a surprise, since the new parameterization substantially modifies the representation of low clouds, which are known to play an important role in climate sensitivity.

6.4 Conceptions of climate models and laboratory cultures

We have seen that modeling groups have different discourses, practices and strategies about the development of climate models. Now I will attempt to better characterize these conceptions, and to clarify what the oppositions really reveal.

6.4.1 Physical understanding, partitioning, hierarchizing

The development of the new parameterization of the LMD model is rooted in a "thought style" (Fleck, 2008) shared by scientists, which is also acquired by young researchers who are socialized within the group, as one of them (L2) recounted:

> At the LMD there's quite a strong lab culture. Even when they're doing different things, they have a common way of seeing things, an approach that's very much based on the understanding of processes, more than elsewhere. [...] I was immersed in it, I became imbued with it. And I also made my own contribution. (L2, pers. comm., December 2013)

As L2 aptly noted, an essential component of the LMD common culture is the importance attached to physical understanding. This conviction was expressed in a position paper presented at a WCRP's conference in 2011 (Bony et al., 2011) written by nine climatologists including researchers from the LMD. The position paper analyses the "Charney report" (a famous report on the effects of increasing CO2 written by a group headed by Jule Charney (1979)) and claim that the reason why this assessment was so "amazingly prescient" 35 years ago is "the power of its scientific approaches," namely "the emphasis on the importance of physical understanding gained through the use of theory and simple models" (Bony et al.: 393).

Understanding is sometimes seen as difficult, impossible or irrelevant in computer modeling: for the philosophers cited above, the "epistemic opacity can result in a loss of understanding " (Humphreys, 2005: 147) and "the holism makes analytic understanding of complex models of climate either extremely difficult or even impossible" (Lenhard and Winsberg, 2010: 253). However, for these climatologists, physical understanding is even more necessary in climate modeling. Morever, it is the precondition of progress in the prediction of climate change:

since the future climate cannot be observed, “confidence in our predictions will remain disproportionately dependent on the development of understanding” (Bony et al., 2011: 404). Thus these scientists assert a convergence – rather than an opposition - between the objectives of knowledge and prediction (Heymann and Hundebol, this volume), and they construct research questions so as to align both concerns.

This common culture manifests itself in discourse and practices, but also in material devices and the organization of the laboratory. Since the late 2000s, the LMD has maintained a panoply of simplified, up-to-date versions of the global model – atmosphere-only models, “aqua-planet” models (entirely covered in water), two-dimensional models, single-column models, etc. – which have simpler climatic systems and fewer variabilities than the GCM (no seasons, no monsoons, no El Niño, no dynamics, etc.), while preserving essential elements. The researchers use this spectrum of models of different complexities at the two “ends” of modeling: in the development of parameterizations (as we saw in the first part) and for overall analyses of simulations – for example, in order to identify “robust” climatic mechanisms, which are found in all configurations, even very simple ones (Stevens and Bony, 2013).

Two approaches that play a major role in the practices and discourses of LMD researchers are the hierarchizing of priority and the partitioning of problems and phenomena. They involve determining what the main climatic mechanisms in simulation analyses are, what elements play an essential role and must be studied in priority (for example, what type of clouds are mainly responsible for model uncertainties (Bony and Dufresne, 2005)), and – as we saw in the previous section – which processes it is important to represent in parameterization. The LMD's new parameterization provides several cases of partitioning: the representation of “thermal plumes” in the boundary layer, for instance, led modelers to distinguish three different scales and to reconsider the boundaries between processes – boundaries that do not exist in detailed modeling, where the transition from cumulonimbus to cumulus clouds is continuous.

These modeling practices – establishing a hierarchy of priorities, identifying the principal factors and partitioning problems into more tractable subproblems – can be seen as ways of circumventing the entanglement of climate processes. Thus for these researchers, the characteristic holism of climate models, rather than making understanding impossible, reinforces the need to invent sophisticated methodologies to work around it (Guillemot, 2014).

6.4.2 Parameterization as Achilles' heel or heuristic tool

How can the different approaches to model development outlined above be characterized? In the article on the "Cloud Parameterization Deadlock" (Randall et al., 2003), the authors find it

> ironic that we cannot represent the effects of the small-scale processes by making direct use of the well-known equations that govern them [and that] cloud parameterization developers […] are trying to compute the statistics of these processes that matter for the large-scale circulation and climate, without directly representing the cloud processes at their "native" space and time scales" (Randall et al, 2003: 1548)

For these authors, there is something scandalous about representing cloud processes using parameterizations instead of using "the basic physical equations in which we have the most confidence... at their 'native' space and time scales." Likewise, it strikes them as almost shocking to separately represent phenomena which are not separated in reality.

The vision that emerges here is of a climate whose entangled processes are governed by the same fundamental laws, and which must be represented in accordance with its real nature, in a continuous and unified fashion. While the dynamic core based on physical laws is the most solid part of climate models, parameterizations, which are incomplete and error-prone, are seen as their "Achilles' heel" – a mere lesser evil to be used until computers sufficiently powerful to solve the equations of fluid dynamics at a small scale become available.

But this is not the only way of seeing the issue. First, calculating atmospheric phenomena from the laws that govern them is not necessarily the ultimate goal of this research. To certain climatologists, on the contrary, it can represent the renunciation of a deeper understanding of processes, as a scientist from Météo-France explained (with regard to the modeling of ocean circulation):

> If you take a model with 2-kilometer resolution, you get beautiful results, which match the observations [...]. But it's frustrating: if we have to solve everything explicitly by computer, that means we haven't understood the physics behind it [...]. We know that sub-grid activity is important in controlling general circulation, but we don't know how to write a transformation law. (scientist from Météo-France, pers. comm, July 2001)

Despite its "beautiful results," this researcher finds something "frustrating" about explicit resolution compared to "transformation laws," which express greater understanding.

Likewise, discourse and practices of the LMD researchers highlight the heuristic role of parameterizations. Rather than emphasizing continuities and unified representations, they emphasize the partitioning of problems, the identification of essential phenomena, the representation of the main processes. “Parameterizing means building the equations and modeling to see if we've understood; if we've taken the key ingredients into account,” according to L2. A parameterization “breaks down the problem and offers an interpretative framework” (L4, pers. comm, July 2012). With detailed explicit models, in contrast, it is more difficult to grasp what processes are at work: “You can't 'unplug' a mechanism to test hypotheses,” unlike with a parameterization, which distinguishes the different processes and coupling variables (L4, pers. comm., July 2012). In brief, parameterizations “sum up our understanding of the system” (L2, pers. comm., December 2013).

That is why some LMD modelers were disappointed by a sort of “ renunciation ” expressed by some of the most renowned scientists working on cloud parameterization. L2 recounted the dismay she experienced at a workshop on climate models where she had hoped to discuss physical questions with eminent colleagues:

> The most shocking thing was the prevailing discourse: “Developing parameterizations is too risky, it’s difficult; it shouldn’t be done.” But that’s exactly what should motivate us, that’s why I did it: it’s open, it’s a challenge! (L2, pers. comm, December 2013)

6.4.3 Confidence in the capacity to pick out the essential

If we try to further specify dividing lines in this area on the basis of the differences that have been highlighted, it emerges that what separates scientists is their confidence in the possibility of picking out the essential processes. Some – including the LMD researchers quoted above – argue that it is possible to identify these elements, using idealized models as an interpretative framework.

This conviction is anchored in a certain vision of the climate: although the climate is complex, it presents patterns, organized behaviors. Despite non-linearity, variability, and the number of factors and processes at work, “it's not just noise, there's an organization to it. There's an object to be studied, we're not aimlessly adding processes,” an LMD researcher said (L6, pers. comm, July 2001). The atmosphere exhibits “dominant modes,” and the job of the climatologist is to identify, explain and reproduce these “simple” structures or behaviors, which requires making use of both simple and complex models. As L6 explained:

> In a certain way nature chooses dominant modes, and we need complex models to go understand how and why [...] But the understanding we get with complex models isn't really well established until we've been able to take it as far as building a conceptual schema. Starting from that complexity, you have to manage little by little to draw out a few simple ideas about how the thing that you're studying works, something you can explain in words [...] And if you master the chain of links between simple and complicated, you think you understand things. (L6, pers. comm., July 2001)

In other words, given that "nature does a simple thing in a complicated way" (Arakawa 2000: 53) these modelers think it is possible to focus on relatively simple aspects of nature's behavior to try and understand that apparent simplicity and reproduce it by modeling it.

Other scientists, on the contrary, are convinced that the complexity of processes and their interactions condemns these attempts at building conceptual schemas. Their view is that "GCMs try to mimic nature's own complicated way of doing simple things" (Arakawa 2000: 53), the model is seen more as a black box, and the work of simplification is delegated to the computer. The search for understanding is not located at the level of parameterizations and their effects, but downstream, at the level of regional climates, impacts, etc.

To put it in terms of confidence (and with some exaggeration): some have confidence in the capacity of climatologists to represent the essential, while others do not. And the latter have confidence in the capacity of complex computer models to approach real climate and predict climate change – which the former doubt, as this LMD researcher (L5) expressed:

> Since the beginning of modeling, there's been this idea that we're going to develop GCMs, increase the resolution, etc., and that naturally we'll approach the solution, the truth. And people realize that it's a long road, really long... But it's an approach that's still deeply rooted for us - an engineering approach perhaps (...) I think that that's not how we're going to get there (...) The way we're going to be able to anticipate something like the solution is much more by understanding what's happening (L5, pers. comm., July 2012)

Still, the possibility of identifying dominant mechanisms within processes, or "simple" relations between climate and processes, raises questions. Can such mechanisms always be isolated? Can the necessary approximations actually be made? The answers will come from the practices of modelers. It may be hypothesized—although that would require further argument—that the capacity to extract dominant processes or to partition phenomena in a useful way depends less on the intrinsic properties of the climate than on cognitive expectations and the way in which questions are asked (Ruphy, 2003).

6.5 Conclusion – Multi-scale practices and cultures of modeling

In this chapter I did not attempt to describe the whole range of positions on the advancement of climate models – that would require a broader study of different modeling groups. Rather, on the basis of the work of modelers in a French laboratory who were developing a new physical parameterization, I tried to draw out some of the factors involved in shaping modeling choices. We have seen here that epistemic conceptions of climate modeling are closely tied to scientific practices: visions of the climate, its complexity, and its predictability are inseparable from the methods and instruments used to study it. These visions, practices, and "epistemic lifestyles" of modelers depend on numerous social and institutional factors, including disciplinary background, research goals, available tools, funding, academic collaborations and research cultures (Shackley, 2001). Strategies for model development cannot be understood independently of these factors.

Among the various social factors involved in scientific choices, the institutional status plays a decisive role. In the case of the LMD, the status of the CNRS was important in making the completion of the new parameterization possible, by allowing scientists to work for several years on a parameterization that they considered important, in a time when this orientation was not considered a high priority – even if it meant, when necessary, to sacrifice publications for some time. These researchers could do without project-based funding, which favors other research pathways. L3, who worked full time for more than ten years on this parameterization, called this "an extraordinary luxury." As L4 declared, "Creating a new parameterization of the boundary layer is unfundable – you have to be at the CNRS to have time to do that kind of thing!"

These choices evidently would not have been possible in all institutional contexts. Researchers propose strategies and adopt "thought styles" (Fleck, 2008) that are in line with expectations within their institution. Rivalries between types of institutions, which have their own instruments, modes of operation, ways of working, and visions of the sciences, play an important role in this context. In climate modeling, it is well known that there is competition between research laboratories and operational prediction centers: the choice of decadal prediction or the "seamless" strategy is often made by researchers working in weather forecasting centers who want to make use of their know-how and expertise from this domain.

These scientists anticipate the expectations of policy makers, who are willing to base their decisions on high-resolution simulations at a decadal or multi-decadal scale (with regard to adaptation, for example; Mahony, this volume). This co-construction is encouraged by funding sources that are inclined to favor the most "technophilic" solutions.

As we saw, the work of modeling involves collaboration on several scales: collaborations with a few researchers from related fields who contribute their expertise; collective work on, around, and with the model, requiring rigorous management; the establishment of research programs within international groups; these activities take place within institutional frameworks that themselves are also multi-scaled.

Especially in climate science, the international level is decisive. This community is characterized by a very strong international structure (which doesn't prevent a diversity of conception and vivid debates), through observational, numerical and institutional global networks and infrastructures – in particular through global research programs like the WCRP or IGBP (International Geosphere-Biosphere Programme). Sub-programs provided an international framework for field experiments, intercomparison projects and the like, but also a collaborative intellectual dynamic. These different levels are evidently not separated by impenetrable barriers, nor are they independent of each other. The same scientists circulate from the laboratory to the national, European or international level, enter into collaborations, attempt to influence a global research program, drive a project or participate in it.

Research in these fields is oriented by diverse and interdependent logics, in particular by technological advances in computing and observation and by pressing political demands. As this chapter has shown, climate modeling is constituted by diverse cultures of prediction, shaped by different practices, institutional priorities, technical capacities, and modes of domesticating the inherent uncertainties and complexities of modeling the climate system. As such, the future of climate modeling is not mapped out in advance, and although certain tendencies seem to predominate, it remains a matter of debate.

Acknowledgement

The research for this paper was financed by the ANR ClimaConf project.

References

Arakawa, A. (2000) "A personal perspective on the early years of general circulation modeling at UCLA," Randall, D.J. (ed.): *General Circulation Model: Development - Past,* *Present and Future*, International Geophysics Series, Vol. 70, San Diego: Academic Press, pp. 2-65.

Dahan Dalmedico, A. (2010) "Putting the Earth System in a numerical box? The evolution from climate modeling toward climate change," *Studies in History and Philosophy of Modern Physics* 41 (3), pp. 282-292.

Bony, S. and J.-L. Dufresne (2005) "Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models," *Geophys. Res. Lett*., 32, L20806.

Bony, S.; Stevens, B., Held, I. et al. (2011) "Carbon Dioxide and Climate: Perspectives on a Scientific Assessment," G. Asrar and J. Hurrel (eds.) *Monograph on Climate Science for Serving Society: Research, Modelling and Prediction Priorities*, Ort: Springer, pp. 391-413

Charney, J. H., Arakawa, A., Baker, D.J., et al. (1979) "Carbon Dioxide and Climate: A Scientific Assessment," Washington, D.C.: National Academy Press.

Fleck, L. (1979) *The Genesis and Development of a Scientific Fact*, Chicago: University of Chicago Press.

Galison, P. (1996) "Computer simulations and the trading zone," in: P. Galison and D. Stump (eds.) *The disunity of science : boundaries, context and power*, Stanford: Stanford University, Press, pp. 118-157.

GCSS Team (1993) "The GEWEX Cloud System Study (GCSS)," *Bulletin of the American Meteorological Society*, 74, pp. 387–399.

Gramelsberger, G. (2010), "Conceiving processes in atmospheric models: General equations, subscale parameterizations, and 'superparameterizations'," *Studies in History and Philosophy of Modern Physics*, 41(3), pp. 233-241.

Guillemot, H. (2010) "Connections between climate simulations and observation in climate computer modeling. Scientist's practices and 'bottom-up epistemology' lessons," *Studies in History and Philosophy of Modern Physics*, 41(3), pp. 242-252.

Guillemot, H. (2014) "Comprendre le climat pour le prévoir? Sur quelques débats, stratégies et pratiques de climatologues modélisateurs," F. Varenne and M. Silberstein (eds.) *Modéliser et simuler. Epistémologies et pratiques de la modélisation et de la simulation*, Paris: Editions Matériologiques, pp. 67-99.

Held, I. (2005) "The Gap between Simulation and Understanding in Climate Modeling," *Bulletin of the American Meteorological Society*, 86, pp. 1609-1614.

Heymann M. and N. Hundebol (2015) "From heuristic to predictive – Making climate models political instruments," this volume.

Hourdin, F., Grandpeix, J.-Y., Rio, C. et al. (2013) "LMDZ5B: the atmospheric component of the IPSL climate model with revisited paramerizations for clouds and convection," *Climate Dynamics*, 40(9-10), pp.2193-2222.

Humphreys, P. (2004) *Extending Ourselves: Computational Sciences, Empiricism, and Scientific Method*. Oxford: Oxford University Press.

Jakob, C. (2010) "Accelerating progress in global atmospheric model development through improved parameterizations – Challenges, opportunities and strategies," *Bulletin of the American Meteorological Society*, 91, pp. 869-875.

Jakob, C., Trenberth, K., Shepherd, T. and D. Bromwich (2010) *Promoting model development*, (White Paper for discussion at the WCRP Modeling Council Meeting), November 2010, Paris.

Knutti, R. (2010) “The end of model democracy?” *Climatic Change*, 102, pp. 395-404.

Lenhard, J. and E. Winsberg (2010) “Holism and Entrenchment and the future of climate model pluralism,” *Studies in History and Philosophy of Modern Physics*, 41(3), pp. 253-262.

Randall, D., Khairoutdinov, M., Arakawa, A. and W. Grabowski (2003) “Breaking the Cloud Parameterization Deadlock,” *Bulletin of the American Meteorological Society*, 84, pp. 1547-1564.

Ruphy, S. (2010) “Is the World Really ‘Dappled’? A Response to Cartwright’s Charge against ‘Cross-Wise Reduction’,” *Philosophy of Science*, 70(1), pp. 57-67.

Shackley, S. (2001) “Epistemic Lifestyles in Climate Change Modeling,” C. Miller and P. Edwards (eds.) *Changing the atmosphere: expert knowledge and environmental governance*, Cambridge: MIT Press.

Shukla, J., Hagedorn, R., Miller, M. et al. (2009) “Strategies: Revolution in Climate Prediction is Both Necessary and Possible: A Declaration at the World Modelling Summit for Climate Prediction,” *Bulletin of the American Meteorological Society*, 90, pp. 175-178.

Stevens, B. and S. Bony (2013) “What are climate models missing?” *Science*, 340(6136), pp. 1053-1054.

---

[1] In practice, the equations in the dynamic part include “source terms” which are determined by the physical parameterizations at each time step and for each grid cell.

[2] “Climate sensitivity” is defined as the temperature change of the surface of the Earth resulting from a doubling of atmospheric CO2 concentration.

[3] Global models rely on “hydrostatic approximation”: that is, they disregard the vertical acceleration of air masses and do not calculate convective movements, which are parameterized. High-resolution models take into account vertical pressure variations and calculate convection using the equations of dynamics.

[4] GCSS is a sub-program of GEWEX (Global Energy and Water Cycle Experiment), one of the principal research programs of the WCRP.

[5] Modeler Christian Jakob compares model developers to an “endangered species.” At a WCRP conference in 2011, he asked the audience of more than a thousand researchers to raise their hands if they had changed their models in the previous two years: twenty hands were raised.

[6] In this chapter, LMD researchers are identified by a letter followed by a number.

[7] White paper on WCRP Grand Challenge. The issue of “Clouds, Circulation and Climate Sensitivity” has been identified by the WCRP as one of the six “Grand Science Challenges” for the next decades. One of its main task is to “tackle the parameterization problem through a better understanding of the interaction between cloud / convective processes and circulation systems.”

[8] A well-known result of climate model intercomparison exercises is that no model is better than the others (a model can be excellent for certain aspects of the climate and less successful elsewhere) and that the best model is often the mean of all models – which is an argument in favor of a multiplicity of models, rather than convergence toward a single model.

[9] The LMD is a laboratory of the Institut Pierre-Simon Laplace (IPSL). The LMD model is the atmospheric component of the IPSL Earth System Model (along with the ocean, biosphere and sea ice components).

[10] The Coupled Model Intercomparison Project (CMIP) coordinates worldwide climate model simulations, whose outputs are synthesized in the IPCC Reports. The IPCC's Fifth Assessment Report (AR5), released in the fall of 2013, is based on simulations performed by twenty modeling groups around the world within the CMIP5 framework.