Studies in History and Philosophy of Modern Physics 41 (2010) 273–281

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

Cultures of simulations vs. cultures of calculations? The development of simulation practices in meteorology and astrophysics

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ARTICLE INFO

Article history:
Received 1 December 2009
Received in revised form
28 June 2010
Accepted 15 July 2010

Keywords:
Simulation
Meteorology
Astrophysics
Computer culture
Practice

ABSTRACT

While the distinction between theory and experiment is often used to discuss the place of simulation from a philosophical viewpoint, other distinctions are possible from a sociological perspective. Turkle (1995) distinguishes between cultures of calculation and cultures of simulation and relates these cultures to the distinction between modernity and postmodernity, respectively. What can we understand about contemporary simulation practices in science by looking at them from the point of view of these two computer cultures? What new questions does such an analysis raise for further studies? On the basis of two case studies, the present paper compares and discusses simulation activities in astrophysics and meteorology. It argues that simulation practices manifest aspects of both of these cultures simultaneously, but in different situations. By employing the dichotomies surface/depth, play/seriousness, and extreme/reasonable to characterize and operationalize cultures of calculation and cultures of simulation as sensitizing concepts, the analysis shows how simulation code work shifts from development to use, the importance of but also resistance towards too much visualizations, and how simulation modelers play with extreme values, yet also try to achieve reasonable results compared to observations.

1. Introduction

From a philosophical perspective, one of the most debated questions regarding simulations is how to situate them in relation to theory and experiment (see e.g. Frigg & Reiss, 2009; Humphreys, 2008; Winsberg, 2008). This is all the more confusing considering that simulation modelers refer to simulations as "numerical experiments", at the same time as they often call themselves "theoreticians" (see also Dowling, 1999). Is the theory–experiment distinction a fruitful point of departure for addressing numerical simulations sociologically as well? This article uses a different framework to discuss numerical simulations and thereby raise new questions of sociological relevance.

Numerical simulations are based on transformations of mathematical models into algorithms, which are then translated into computer code (Winsberg, 1999).[1] I refer to these computer programs as simulation codes and to those who build and execute ("run") the program that performs the numerous calculations (the simulation) as modelers. Because of the basis in computing, numerical simulation activities are part of particular computer cultures. The present article takes its point of departure in the classification of computer cultures as cultures of calculation and cultures of simulation (Turkle, 1995) and applies these as sensitizing concepts to explore contemporary numerical simulation activities in meteorology and astrophysics.[2]

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[1] Computer simulations in the physics based sciences tend to reduce the full complexity of the phenomena under study to a small number of physical laws and it is the related equations that define the dynamics of the system, but ad-hoc expressions and adjustments are included into the model for computational

(*footnote continued*)
reasons. If we consider the mathematical model and the computer program—the code—as two forms of a highly complex technological object, scientists performing numerical simulations spend at least as much of their time working with the code (programming, etc.) and related software packages (such as visualization tools) rather than with the model (working on equations, setting parameters).

[2] Previous STS literature on astronomy has mostly focused on observations and use of telescopes and satellites (see e.g. McCray, 2000; Krige, 2000). Kennefick (2000) is an exception by analyzing a controversy around results based on numerical simulations (referred to as "theoretical" work) in astrophysics. There is a richer literature on simulations in meteorology, both regarding current practices (see e.g. Fine, 2007; Sundberg, 2006, 2009) including climate modeling (see e.g. Edwards, 2001; Lahsen, 2005), and its historical development (see e.g. Nebeker, 1995; Harper, 2008).

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doi:10.1016/j.shpsb.2010.07.004

Sensitizing concepts give a general sense of reference and a way of seeing (whereas definitive concepts are clearly defined in terms of attributes or fixed benchmarks) (Blumer, 1969: 148). Thus, the overall question is what these two ideal types of cultural forms, which implicitly tie the analysis to more general cultural trends in contemporary society, shed light upon regarding contemporary simulation activities in science. Is it feasible to consider numerical simulations as shifting from one of these cultures to the other? On the basis of two case studies of numerical simulation practices in meteorology and astrophysics, the purpose of the present article is to explore where the notions of cultures of calculation and cultures of simulation lead us and to suggest where to look further.

In the following, I present the notions of culture of calculation and cultures of simulation (Turkle, 1995). In order to apply them as sensitizing concepts, I break them up into three dichotomies. After presenting my data collection method, material, and analytical strategy, I apply the dichotomies to particular numerical simulation activities, and related situations, in meteorology and astrophysics.

2. The characteristics of cultures of calculation and cultures of simulation

The culture of calculation is modern and characterized by linearity, logic and depth, and there is a promise to explain, unpack, reduce and clarify its outcomes (Turkle, 1995). For the computer considered as a calculator, this means that what happens inside it can be (mechanically) unpacked. If we apply this conceptualization of the modern to numerical simulation activities it implies developers/constructors who build their codes by and for themselves. When analyzing the outcomes of simulations, they unpack the computer programs to reach the underlying mathematical model.

Postmodern culture of simulation is fluid, decentered, and opaque and search for mechanisms and depth is futile (Turkle, 1995). The boundary between the virtual and the real is eroded, both in everyday life and in scientific fields. We can simulate nature in a program or build second natures where the objects visualized on the screen have no simple physical referent (cf. Helmreich, 1998). Images have been highlighted as a crucial aspect of postmodern society and visualization is one of the major themes in Turkle's (2009) more recent collection of essays on simulation practices. However, Frigg and Reiss (2009) note that visual representations are not particular to simulations and that dynamic (such as cinematic) representations, contain exactly the same information as a (static) table or plot, but that the former may be easier grasp. They dismiss this special feature of simulations from the realm of philosophical interest, yet there might be sociological implications and consequences worth discussing. For example, the presentation of visual material in the form of animations compared to discussion of equations can be regarded as manifestations of the distinction between surface (culture of simulation) and depth (culture of calculations). Do animations invite us to look, rather than think (cf. Jin, 2008: 147)? Are they entertaining rather than evidential and as such serving to seduce scientists to overestimate the credibility of simulations (cf. Baudrillard, [1970] 1998; Lahsen, 2005; Turkle, 2009)?

Importantly, Turkle (1995) emphasizes the shift from programming to use of computer programs which took place from the 1970s through the 1990s and she describes the user as someone seduced by the interface and involved with the machine in a hands-on and applied way, not interested in *why* technology works, but only that it works.[3] Because such a shift from construction and development ("depth") of simulation codes, involving writing equations, adding new modules, coding, programming etc., to use ("surface") as black-boxes without paying much attention to the inside is a basis for cultures of simulation to evolve, it is of elementary importance to take it as a starting point for analyzing the work with simulations codes in science too.

Moreover, a postmodern approach implies playful exploration at the interface rather than serious, in-depth investigation (cf. Jameson, 1984). Play in the common sense meaning used here refers to engagement in activities for enjoyment, rather than for serious or practical purposes. Thus, the dichotomy seriousness/play characterizes the modern vs. the postmodern. Yet from a sociological viewpoint, play is commonly regarded as a part of socialization (see e.g. Mead, 1934). To distinguish among the modern and the postmodern I therefore draw upon Baudrillard to propose that they are characterized by different playful attitudes. Baudrillard ([1970] 1998: 114) refers to passion as a playful attitude consisting of sincere desire and a concrete relation to an object which implies total investment and intense symbolic value, whereas the playful attitude of mere curiosity is more volatile and characteristic of the consumer (postmodern) society. If contemporary culture is marked by preference for extremes (Baudrillard, ([1970] 1998; cf. Bogard, 1990), extremeness might be required to create curiosity. For modelers, such a preference would imply that they no longer seek to generate simulation output that appears reasonable in relation to the real world (cf. also Turkle, 2009: 56f.), but amuse themselves with extreme, rather than reasonable, scenarios instead.

To summarize, cultures of simulation and cultures of calculation can be characterized by the dichotomies surface/depth, play/seriousness, and finally, extreme/reasonable. They are used to discuss how these "cultures" exist *side by side* as manifested in different simulation *activities and situations*, not as characterizing whole fields or generations of scientists. However, indications of shifts in emphasis over time can be observed.

3. Methodological considerations and material

Meteorology and astrophysics are two physics-based sciences where traditional experiments are impossible to conduct and numerical simulations play an important role, enabling "numerical experiments". Strictly speaking, astronomy is the science of measuring the positions and characteristics of astronomical objects and astrophysics is the application of physics to understand astronomy, but nowadays the two terms are interchangeable since all astronomers use physics. Among the practitioners, "astronomers" often refers to those making observations whereas "astrophysicists" refer to those working with theories, models and/or numerical simulations. While astronomy is one of the oldest sciences, meteorology developed from a marginal scientific backwater to a rigorous science in the last century and this was mainly due to numerical weather prediction (Harper, 2008), but importantly, meteorology is also an academic discipline focusing on understanding the physics and chemistry of the Earth's atmosphere.

The themes in the theoretical section structure the comparison of the cases in order to present a fresh view on how simulation activities in these two disciplines differ, but also what they share. Attending to shared features is important because it is first by establishing similarities that we can note differences. Notably, I disregard the content of knowledge in these disciplines (e.g. processes in Earth's atmosphere or in the Universe) and exclusively focus on the form of numerical simulation-related activities taking place in a number of situations. Practitioners

[3] I do not raise any conceptual discussions on user/developer here. See Oudshoorn & Pinch (2007) for a general discussion and Sundberg (2010) for analysis of how the distinction between users and developers of simulation codes can be understood on the basis of how work is organized.

develop ordered views and conceptions—perspectives—as they enter typical situations and indulge in related activities and people may hold different, even contradictory, perspectives depending on the situation (cf. Becker, Geer, Hughes, & Strauss, 1961; Shibutani, 1955; Becker, 1982).

My primary sources for understanding these perspectives are interviews and participant observation, mainly conducted in Sweden.[4] Additional, secondary material includes web page information, scientific articles, and course material. I offer insight into my material and illustrate points by providing references to the secondary material as well as quoting from interviews and field notes. Because the secondary material is mainly used as confirmation of what has been concluded from the primary sources, the list of references to this material only includes what I explicitly refer to in the main body of the paper.

I have interviewed eight meteorologists and eleven astrophysicists working with simulation codes.[5] Of these 19 interviewees, there were five doctoral students, two post-doctoral students, seven research scientists, and five professors. Eight of the interviews were conducted in English, the rest in Swedish. Citations from these interviews have been translated to English. To protect the identities of the informants, I do not inform when this has been the case. The recorded interviews concerned activities such as programming, interpretation of results as well as how to deal with and reason around everyday problems.

At their research departments, modelers work alone in front of their computers, occasionally writing equations on a piece of paper. To observe hands-on work with the keyboard is not necessarily fruitful unless you know and understand very well the effects on the screen (see also Sundberg, 2005: 221f.). Presentations at colloquia, workshops, etc. are better sources for material on how simulation modelers interact. Consequently, observations were primarily conducted in more formal (front stage) settings compared to the activities taking place to prepare for these settings (back stage) (cf. Goffman, 1959). During two meteorological conferences, I attended 50 presentations in total. Observation at a workshop included attendance during 17 presentations. For the astrophysics case, I attended 20 presentations during one symposium. During three simulation code user meetings in astrophysics, I attended a total of 22 "science" presentations (in addition to "code" discussions). I also attended many of the informal events related to these different gatherings. Additional observations occurred during seven departmental colloquia in astrophysics and six departmental colloquia in meteorology as well as two dissertation presentations and defenses in astrophysics and three in meteorology. I also attended six (out of ten) days of an interdisciplinary doctoral summer school on multi-scale modeling and simulation. Astrophysicists and meteorologists participated both as teachers and students during this course.

All the gatherings I ventured were directed towards a scientific audience, either meteorologists or astrophysicists. Thus, presentations exhibit how modelers show their work to other scientists, who are often, but not always modelers themselves. Questions from the audience indicate their expectations and perspectives as well as give insights into what modelers discuss, debate or even disagree upon. In addition, they serve to verify what interviews have revealed about activities and perspectives. During every talk, I noted the presentation of simulation codes, the equations underlying them, the type of visualizations used to present results, and the dialog and discussion taking place.[6]

Surface/depth, play/seriousness, and extreme/reasonable are simple dichotomies attempted to concretize what cultures of simulation and cultures of calculation imply if we look into different simulation activities and situations. In the following, I focus on how modelers use or develop simulation codes in their work, and in particular what doctoral students do. Socialization makes a person learn how to approach the world from the perspective of her reference group (Shibutani, 1955). In science, specific skills, philosophies and commitments are acquired at the doctoral level, when the doctoral student learns the necessary skills to become a scientist (cf. Bucher, 1965: 197, 203). This has two important implications. First, the socialization of the doctoral students into the practice of simulation modeling involves adopting the perspectives of the researchers they are surrounded by, and this means that if handled carefully, their accounts can be analyzed as expressions of similar, evolving perspectives as well. Second, socialization activities indicate how practices develop and change, for example, by showing what skills a scientist is supposed to have apprehended. Possible shifts are therefore interesting, in spite of focusing contemporary conditions. I then move on to how modelers present their work during conferences, colloquia, and such, in order to discuss imagery and visualizations. Finally, I connect the interpretation and evaluation of simulation output in different situations to different sorts of playfulness. The analysis mentions various activities and these may appear as interesting to dig deeper into, but because of the aim to be exploratory and suggest more specific questions for further inquiry, they necessarily remain described in a sketchy fashion in the present paper.

4. Socialization through superficial use or in-depth development

The balance between design and use is a fundamental aspect of computer culture, hence a motivation for the analysis to set off here. Like computer programs in general, the possibility to use simulation codes as an off-the-shelf tool has increased over the past few decades. Some simulation codes are still only accessible to those who developed them or to members of a particular organization, but many codes are publically accessible, generally provided through web pages of the founding institute or scientist (Sundberg, 2010). For example, one web page for "simulating astronomers" lists 16 free simulation codes (see http://astro-sim.org/content/view/15/29/), but interviews and observations indicate that only three or at most four appear to be widely used. In meteorology, it is primarily different versions of one particular American weather forecast code (Weather Research and Forecasting model or its predecessors) that reappears in presentations and several informants have mentioned that this code is extensively used. Yet most presentations, both in astrophysics and meteorology, are based on utilization of a code that the speakers have contributed to develop or whose close colleagues have done so.

However, qualitative interviews and observations at most indicate how common it is to download free code. Quantitative material is required to draw conclusions regarding frequency. To focus on the tasks that doctoral students who will work with simulations start with is another way to approach whether use is

[4] See the appendix for detailed lists of interviews, the affiliation of the informants and the dates when they occurred as well as of when and where I conducted observations.

[5] To my knowledge, three of the astrophysicists and two of the meteorologists had or were also observing.

[6] I do not analyze visualizations per se, but how they are incorporated into presentations. See Turkle (2009) for more general discussion on visualizations (and simulations). On the analysis of visual representations in everyday practice, see e.g. Lynch & Woolgar (1990).

about to increase in relation to development. If socialization increasingly occurs through use, this is a sign of a general shift, especially since people in higher positions generally work with interpretation of output rather than with development (like tinkering with measurement instruments in the lab is a typical student task).

Previously, modelers started their career by writing a code "from scratch" or by making major developments to an existing simulation code. At least this is what senior modelers report. However, it remains uncertain whether these were the *best* ways to start an academic career—and if this is why they are still in academia—or if development was the *only* way to start (cf. MacKenzie & Millo, 2003: 111f.). For example, no infrastructure such as the Internet enabled distribution and sharing of codes before.

Today, there are basically three different ways of training doctoral students to work with simulation codes in meteorology and astrophysics: (1) to develop a new code, (2) develop a new part of an existing code, or (3) use an existing code as it is. The first and the second approaches are often combined. One constructs a completely new, stand-alone piece of simulation code. This is then implemented as a new component into an existing simulation code (which has often been built by the doctoral student's supervisor). One of the major purposes of getting into the dirty work of programming and debugging is to gain a deeper understanding of the technique of simulation codes. These tasks take time. In one email, an astrophysicist described his doctoral work consisting of the implementation of a new algorithm. He concluded: "It took a few years of code development, which was *costly* because time spent writing code was time lost from performing numerical simulations and publishing papers" (emphasis added) (cf. Ribes & Finholt, 2009: 384, 387). Importantly, *model* development including such aspects as introducing a new algorithm is prestigious, but rare, while papers presenting developments of the *code* which does not involve changes in the fundamental physics count as second-class articles ("method papers"). They are commonly published as working papers or user manuals, as opposed to as articles in journals.

Because of the lack of prestige regarding code development and the time and resources that are required to develop a simulation code, it might therefore seem like a better career investment to focus on use (cf. Shibutani, 1955: 567), download another code from somewhere and get regular updates for free, so to speak. This is motivated by comments such as "everything is already in there" or "why invent the wheel twice?" Doctoral students who receive or search for a ready-made off-the-shelf simulation code only take responsibility for "setting up" the simulation. They therefore do not examine computer code as closely. There is black-box usage of simulation codes in astrophysics as well as in meteorology and users in both disciplines express their appreciation of the possibility to apply codes to scientific problems without caring much about how the codes are built inside. For example, during one symposium (meeting A1), one doctoral student in astrophysics told me how he applied a well-known, widely distributed astrophysics simulation code to his problem. He thought it was very easy to use and said that if you wrote the type of problem you wanted to do, e.g. "hydrodynamics", the computer code could choose the required "solvers", even if you did not know exactly which parts of code were necessary for a particular simulation. (In some well-developed, modular codes available in both meteorology and astrophysics, the user can "switch" parts on and off depending on what is necessary for a particular simulation, but there is no requirement to code.) This astrophysicist was content to conclude that one "can get results", without a deep knowledge of the innards of the simulation code. Yet some are less content with this possibility (cf. Turkle, 2009). It is striking how astrophysicists who have developed codes often pass comments, complaints and warnings about the dangers of using simulation codes as black boxes, both in discussions among themselves and during interviews. Because of fewer complaints, this type of usage appears as somewhat more common and accepted in meteorology compared to in astrophysics.

A fourth way of socializing into meteorological simulation practices—without ever "running" a simulation!—supports the claim that black box usage is more accepted in meteorology: Several recent graduate projects at the largest meteorological university department in Sweden (Department of Meteorology at Stockholm University) are based on analysis of output from the climate models participating in the coupled model intercomparison project, CMIP (see e.g. http://cmip-pcmdi.llnl.gov/; Meehl, Boer, Covey, Latif, & Stouffer, 2000; Covey et al., 2003).[7]

Before discussing CMIP, let me briefly explain the idea behind intercomparison projects. The primary aim of intercomparison projects is to compare the results of numerical simulations of the same type of scientific problem or case. Different simulation codes, each "ran" by a different researcher or group, are prepared to perform the same numerical simulations and results are then compared, discussed, and finally presented in one or several publications. This type of project has become common in both meteorology and astrophysics.[8]

Within the framework of CMIP, model intercomparisons have been organized three times and a fourth round is on its way. Climate models require great resources to be developed, "ran", and interpreted and as the question of global warming gains more attention both in science and in politics, there are increased demands on what processes (physical, biochemical as well as biological) that output data should be able to answer questions about, which means that increased demands on the number and type of process descriptions that have to be included in climate models. These are some of the reasons why only about twenty climate models, from the most prestigious climate model centers in the world, have submitted results of their simulations of similar scientific problems (climate scenarios) to a common database. Several hundred articles have been published only on the basis of data from the third CMIP, *many by scientists and groups who did not provide data themselves* (see e.g. http://www-pcmdi.llnl.gov/ipcc/subproject_publications.php). These articles commonly approach some research problem by "evaluating" the mean values of some parameters from the different climate model simulations, sometimes also their individual results, compared to observations or so-called re-analysis data (see Section 6). The major purpose of this is therefore neither intercomparisons of not deep analysis of output from the individual climate models, but these models together constitute what is referred to as an *ensemble* (see also Edwards, 2010: 284, 354; Parker, this issue). The feature of CMIP which is interesting with regard to the present analysis is therefore that users of the CMIP-database stay at the interface level of simulation codes, totally detached from the numerical simulation and the code as the source of production of output. For example, one doctoral student said: "In these studies it is kind of that the models are felt more like black boxes and then there are *things coming out* (...) Here you just take them, here it's *only a result*." (Interview M4, emphasis added).

[7] Astrophysicists often refer to simulation codes as "codes", but meteorologists switch among "models" and "codes", even if they refer to a version of a computer program. Because climate model is a widely used term for the simulation codes used to simulate climate, I make an exception and stick to this terminology regarding what would be more adequately referred to as codes.

[8] See Sundberg (in press) for an analysis of intercomparison projects.

The so-called Millenium simulation appears as somewhat of an astrophysical equivalent to CMIP3 in terms of offering astrophysicists the opportunity to take output from a database, analyze, and publish papers on the basis of it, without having been involved in the simulations themselves (see http://www.virgo.dur.ac.uk/). The simulation is one of the "largest ever" of the formation of structure in the universe. It is an outcome of the Virgo consortium, which is an international collaboration among scientists from roughly the same countries as those that have important climate modeling centers (the UK, Germany, the Netherlands, Canada, the USA, and Japan). In terms of usage of the dataset, this effort also seems to have been a success. The Millenium simulation homepage currently lists 243 articles, written by astrophysicists all over the world, "that have directly used the Millennium Simulation data, and that we spotted on the astro-ph preprint server" (see http://www.mpa-garching.mpg.de/millennium/#VISUAL_MATERIAL). However, the title of these publications and several abstracts show that Millenium output is used to contribute to (initialize, compare, etc.) some other calculation rather than analyze itself. Another major difference compared to CMIP is that the Millenium simulation was produced by using one particular simulation code and it had nothing to do with intercomparisons of codes. Compared to the use of data from CMIP, the Millenium simulation is not obviously a sign of the "superficiality" of a culture of simulation.

Importantly, the purpose of discussing CMIP and the Millenium simulation is to show the move from developing simulation codes and "running" them towards use of output data that one has not even produced oneself; a possibility that has been opened through archives where output from complex simulations is accessible as datasets for anyone who might be interested in exploiting it. As an example of "surface", this indicates a shift towards a culture of simulation rather than calculation. Looked upon from a different angle, these efforts could of course deserve more attention in themselves, but this is beyond the scope of the present paper.

5. Entertaining surface vs. boring depth: "movies" and equations

Visualizations of simulation output is important to acknowledge in relation to the distinction between cultures of calculation and cultures of simulation and also in relation to the usage orientation discussed above. In the following, I describe how visual material (representing surface), primarily in the form of animations, and equations (representing depth) are presented and discussed during scientific talks. The aim is not to provide new empirical knowledge as much as it is to continue the application of the dichotomies that have been formulated to discuss numerical simulations as cultures of calculation or simulation.

Due to the focus on usage of animations, meteorology remains in the background—at first. This is because the most significant form of visualization that meteorologists use to present their results—in addition to plots and diagrams—is colorful maps. Meteorology is pervasively cartographic and maps are the conventional way to visually present meteorological results, whether they derive from observations or simulations (Monmonier, 1999). Interestingly, although meteorological research *practices* have developed, not least through the use of computers for "calculating the weather" (cf. Nebeker, 1995), the *form* of visualizations (maps) seems to have remained the same. However, there has been a remarkable improvement in the sophistication of these maps as well as difficulties in implanting new imaging technologies (cf. Monmonier, 1999). While this is certainly an interesting topic for separate analysis, it is beyond the scope of the present article.

In astrophysics, presentations commonly include two or three dimensional "movies". For a minute or two, these cinematic representations visualize simulations of phenomena such as rotating gas disks or development of a magnetic field in a star. At various occasions, astrophysicists, and especially junior modelers, referred to animations as "impressive". When I asked astrophysicists about why they show movies, the answer they gave was that they wanted to "entertain" their audience. In fact, they also seem to serve the more modest purpose of catching attention. During my observations at astrophysical colloquia, some astrophysicists who did not provide animations to illustrate their simulation results explicitly excused themselves for not showing "movies" and during the various meetings I attended, it was striking how little interest the audience seemed to pay to the presentations. While those attending colloquia at least appear to listen to the presentation and look at the speaker, the part of the audience that appears to attend to the speaker during larger meetings—rather than look into the screens of their laptops and tapping on the keyboard—is small. In addition, presentations partly motivate the creation of animations in the first place, which is another sign of how these are related to front stage activities. Many astrophysicists view animations as giving a rough idea of what is happening in a simulation; animations do not serve as basis for in-depth analysis. One doctoral student said there are "much more powerful diagnostics" (Interview A6)—supposedly used back stage. Furthermore, some astrophysicists also express their worries about the visual development, especially how "fancy 3d movies" convince audiences, supposedly for the wrong reasons (cf. Lahsen, 2005: 911; Turkle, 2009: 77ff.). For example, they emphasize how visualizations—a form of output and as such representing surface—cannot be separated from the equations, data etc.—the inside representing depth. This implies that the value of the former has to be evaluated in relation to the character of the latter. For example, one doctoral student in astrophysics said:

> Now you start to get all these numerical results and you can do flashy graphical pictures of how things would look like... and you could sometimes, those who simulate galaxies for example, then they show their results graphically and it really looks like a galaxy with spiral arms and that then, really cool, really. And then you may get the impression that this numerical model is completely superior everything that's done analytically. But that's not how it really is. But it is based on how much relevant information you put in. (...) An analytical model doesn't give a flashy image of a galaxy, but it most often gives an equation. (...) Here, all of a sudden, you get a really stunning image that looks exactly like a galaxy. (Interview A3)

The quote illustrates the view that visualizations make simulations appear more "realistic" and therefore superior to the results of "analytical methods", based on the writing of formulas and pen and paper calculations (at the same time the type of images we consider as realistic and "looking really like" something is obviously a matter of aesthetic conventions). Because of the double-focus on cultures of calculation as well as cultures of simulation, the following discussion revolves around the distinction between the outcome of "analytical methods" (equations) and simulations (images) and the role of equations and visualizations in presentations *vis à vis* each other.

Modelers often refer back to the equations of the model underlying the simulation code when the audience requires explanation or justification of results (cf. Kennefick, 2000, see also Sundberg, 2006). One astrophysicist referred to this habit as "old fashioned" and in the following quote, he expresses his critique explicitly:

> I don't think there are enough people using visualizations. There are many I've talked to about, for example, dynamo theory which I have worked with and they say that yes, but the equations look like this and that leads to this. Even if they do big numerical models, they explain what happens in that they point at the equations and say that this does this and this, not at the physics, not at what actually happens. (Interview A10)

Rather than to "point at the equations", this astrophysicist advocates analysis of visualizations. Whereas the previously discussed quote emphasized that output from a simulation code depends on its *input*, implying that it is actually the equation which is most important, the last quote encourages focus on *output*, not the equations. This plea for focus on visualization is another indication of a shift towards a culture of simulation where one stays at the surface, as opposed to a culture of calculation that seeks to explain and unpack by looking back into the (depths of the) equations. Interestingly, the two last quotes illustrate almost opposite views: On the one hand, skepticism towards elevating simulations are compared to analytical methods on the basis of seductive qualities of visualizations compared to equations. On the other hand, the second view proposes more analysis of visualizations at face value, without returning to underlying equations for justification.

However, it is important to note that equations are not only introduced to defend and explain results (including visualizations of them). In the context of presentations, equations may also introduce the simulation code itself, before discussing the output data the simulation "run" has produced. In presentations of meteorological simulations, simulation codes are often presented by use of their names (acronyms) (and they are referred to as "models", see also footnote7). They are described with words rather than with equations; listing characteristics such as for example "hydrostatic", "sigma-*z* vertical coordinate" and "C grid". Sometimes there is information about what "schemes" they include for taking representations of sub-grid processes such as turbulence and cloud formation into account. When I talked with some meteorologists at a conference (Meeting M3) why there was so little said about the underlying equations, they replied that there is no point to "waste time" to talk about them because they are so similar. The "core" of the models generally consists of the so-called Navier Stokes equations.[9] While these can be solved in different ways, current discussions and debates concentrate on how to formulate the various "schemes" (see also Sundberg, 2007, 2009).

Thus, the underlying equations are to some extent taken for granted and unquestioned, but the taken-for-granted is always related to particular groups of people. For example, a one-week-symposium (Meeting A1) gathered astrophysicists working on planets, stars as well as the structure and history of the Universe (cosmology). After about a day of presentations, one participant asked the speakers to be explicit about equations and implied that it was "okay" to exclude "if you talk to your own community", but that this was not the case here. This indicates how bringing equations back in may be a way for modelers from different fields to communicate with each other. More generally, my observations reveal that especially astrophysicists often start to write equations when they speak to each other casually, suggesting that equations are important in back stage conversations. On the front stage however, there were modelers, both in astrophysics and meteorology, who excused themselves for showing equations on their power point slides. Thus animations seem to be used as a way to catch attention, whereas astrophysicists said that equations "bore" the audience.[10]

The present section illustrates how astrophysics presentations appear more "modern" than meteorological counterparts regarding attempts to unpack simulations and codes into the underlying equations. At the same time, the use of and discourse on animations signal inclination towards "postmodernity" in astrophysics, but not necessarily seduction. Meteorology is just as visual as astrophysics, and meteorological presentations stay on the surface to an even larger extent—in the sense that equations rarely appear. Perhaps one reason for this is that it is actually comparison to observations that serves to justify results, rather than turn to underlying equations. This is discussed in the final part of the analysis.

6. Playing with the extreme or making output reasonable

The two previous sections focused on the distinction surface/depth regarding use/design and visualizations/equations. In this section, I shift emphasis and discuss educational as well as "experimental" simulations in relation to the dichotomies play/serious and extreme/reasonable.

When prearranged simulations serve as teaching tools of simulation codes, they do not necessarily represent plausible scenarios. For example, during a summer school in multiscale modeling and simulation, students had to choose a particular research project to work on together with an expert in that field (climate dynamics, turbulent dynamos, quantum mechanics, etc.). The climate modeling project was introduced by a meteorologist as a "wild experiment to see how you get complete ice-cover" on Earth. The intention was to make the students "get a feeling" for the simulation code and understand it, not to generate plausible scenarios. Frequently, instructors facilitate the understanding of a simulation code and its output through extreme settings.

In addition to these playful ways of *learning* how to handle simulation codes, are numerical simulations also conducted in playful manner more generally? Importantly, senior astrophysicists spoke openly and spontaneously about playing and told me that it was common among doctoral students. For example, one professor in astrophysics said: "If you would go over in the corridor where most of my students sit and you would follow their work for a day you would sort of see that there is a distinct element of play". (Interview A2) But what is played with and in what context is the activity referred to as play taking place?

Curiosity for the simulation code, expressed through play with "strange" results in order to get to know it, is a part of the socialization process into numerical simulations methods because it makes you learn how codes work. The perspective is accepted if it is part of this learning process, but not to the same extent if it develops into more like a *passion* for the code as such

[9] The Navier Stokes equations describe the motion of fluid substances. These equations arise from applying Newton's second law to fluid motion and are used not only to model the weather, but also for applications in, for example, astrophysics to model the motion of stars inside a galaxy (as well as in many other areas).

[10] For example, some minutes into a presentation at an astrophysics meeting (A1), the speaker said: "Sorry, I have to bother you with all the equations, but I think most of you are theoreticians and the observers have already fallen asleep." In the quote, modelers are referred to as "theoreticians", whereas "observers" refer to the astronomers who observe heavenly bodies. The excuse supports the suggestion that modelers view equations as "boring" to show, at the same time as the quote indicates that it is at least acceptable to present them among peer-modelers. "Observers" were assumed to lack interest in the presentation all together. One astrophysicist (Meeting A3) motivated his use of animations by telling me that "many at my institutes are observers and they don't benefit from equations" (cf. Sundberg, 2006: 61), as if animations would be especially useful in order to communicate with them.

(cf. Baudrillard, [1970] 1998: 114). For example, during an informal discussion with some other astrophysicists (meeting A1), a recent Ph.D. said that there is a "danger" in computational astrophysics of "getting stuck" in simulation code development because you "fall in love with the computers", "stop doing science", and become a "system administrator", referring to those who continued to focus on simulation code development for the sake of the code itself (cf. Turkle, [1984] 2004: 20; 1995: 30–33).

To play around to get to know the code (a learning context) is, at least in principle, quite different from playing with extreme scenarios to understand, for example, phenomena in the Universe as target systems for simulations (an experimental context). Generally speaking, implausible simulation results such as e.g. negative energy levels are regarded as problematic and due to errors that have to be fixed. Interestingly however, astrophysicists do not always perceive unrealistic outcome as *only* problematic. One professor in astrophysics said the following:

> If the program starts producing things that look interesting but strange, then you can work in different ways. You can say that I don't think reality is like this so then I have to get rid of this and then you go and look. But you can also do the opposite and say this was funny, I wonder how I can make the program produce even stranger things? And then you trigger this, perhaps find some property of the program or the equation, that makes it become very strange although you remove yourself from reality. You know you remove yourself from reality, but it does not prevent you from trying to study the phenomenon and refine it. (Interview A2)

This account illustrates how the modern and postmodern exist side by side by distinguishing between two opposite approaches to "interesting but strange" results. First the modern, serious oriented towards realism ("I don't think reality is like this so then I have to get rid of this"), then the more postmodern and playful, implying a curiosity for the extreme ("this was funny, I wonder how I can make the program produce even stranger things?"). The astrophysicist talks about the fascination for strange things just like Turkle ([1984] 2004: 143) discusses how adolescent children delight in spectacular screen effects. Simulations create the feeling of enchantment about something that differs from ordinary science aimed at investigating plausible results, as opposed to "strange[r] things".

Another example of how results with "no physical meaning" are not always referred to in negative wording is the following quote from a doctoral student in astrophysics: "You can find yourself in situations when you get a result that doesn't have any physical meaning. You get some very interesting output, but it has no physical meaning, it's a pure numerical artifact." (Interview A3) If the aim is to understand phenomena in the Universe, it might seem absurd to view a result without "physical meaning" as "very interesting". Yet this quote does not necessarily imply a turn to the exploration of a "second nature" (cf. Helmreich, 1998) but rather a focus on the *simulation code*—possibly as a part of socialization (learning). If it is the simulation code that one seeks to understand, these types of results are also meaningful, even if they are not considered as plausible descriptions of the real world.

Whereas playing with extreme scenarios to get to know the code occurs in both astrophysics and meteorology, it appears restricted to strictly educational activities in meteorology. To my knowledge, meteorologists do not slip into speaking about (what is perceived as) "unrealistic" output as anything but problematic. Meteorologists rather speak (and write) of their simulation output in terms of "bias", "over-" and "underestimation" compared to some reference, usually observations or observation-based products. Thanks to the resources invested in weather forecasting, there is a huge measurement network that provides meteorologists with data on temperature, wind speed, wind direction, cloud coverage, pressure, etc. in the order of several millions of observations per day (see e.g. Edwards, 2010). Modelers complain about the incompleteness, uncertainty, and bad quality of observations, but they are nevertheless expected to compare their output with them (Sundberg, 2006).

In astronomy, observations are mainly received from detection of electromagnetic radiation, including visible light, from different regions of the electromagnetic spectrum, primarily through the use of telescopes. Astrophysicists share with meteorology the *aim* to compare their simulations with observations, but during the astrophysics talks I have attended, almost no presentation included comparisons to observations.

Among meteorologists, most talks included comparisons. They often juxtaposed simulation output and observational datasets in diagrams or snapshots, etc. where different colors or shapes indicate what represents output and what represents observations. However, like Lahsen (2005) observed regarding climate modelers, meteorologists often mix up observation data and output, in conversations as well as in charts during presentations. Blurring is even more pronounced regarding so-called *re-analysis* data. Re-analysis yields a spatially and temporally coherent dataset over the past, global state of the atmosphere by using fixed, modern versions of data assimilation systems developed for numerical weather prediction and re-analysis and data assimilation is commonly referred to as a "synthesis" of models and measurements.[11] Observations are manipulated and recombined to offer data which is suitable to compare with simulation output, primarily because of the spatial and temporal coherence it shares with—indeed is a result of—the modeled representation of the atmosphere. On the one hand, the heavy use of observations for comparative purposes could be referred to as maintenance of the "reality principle" in meteorological simulations (or as a focus on the atmosphere as the target system). On the other hand, production of re-analysis indicates the precession of the model—simulacra—because it involves explicit and overt adaption of the observations to the models (cf. Baudrillard, [1981] 1994; see also Edwards, 2001). Re-analysis is therefore an example of how features of cultures of simulation or cultures of calculation appear as significant depends not only on what activities that one chooses to focus on, but also on what particular aspect or context that is shed light on.

7. Concluding remark

The present analysis draws upon Turkle's (1995) distinction between cultures of calculation and cultures of simulation to select and highlight features of contemporary numerical simulations. In her more recent book *Simulation and its Discontents* Turkle (2009) focuses exclusively on "simulation" and asks what it *wants*, but the characterization of "simulation" in science is broad-brushed. In spite of the vivid essays, the book leaves unclear what "simulation" means, in part because the wide range of computer-based activities

[11] In meteorological simulations for research purposes, very little data is used during initialization, i.e. the start-up of a simulation when the computer model uses some input-data in order to start calculations. For forecasting purposes, data from the observational network system of satellites, radio probes, weather stations, and aircraft are assimilated. Observation data cannot simply be "fed" into the computer for use in numerical simulations without consideration, partly because they are not measured at the right time or right place compared to the model's temporal and spatial scale. The model always starts with something which is referred to as "first guess", which is generally the previous forecast. If the "first guess" would be neglected, observations are considered to destroy the balance of the model. Observations that are too far away the first guess of the forecast are therefore not used, whereas the rest is assimilated.

that seem to be used as examples of the phenomenon. Furthermore, and as its title indicates, *Simulation and its Discontents* exclusively focuses on (cultures of) simulation, but also the dissatisfaction with it (see also Helmreich, 1998). The present analysis contributes by presenting a more systematic view of numerical simulations in two physics-based disciplines through the lenses of cultures of calculation and cultures of simulation. The entry of numerical simulations into the scientific enterprise has many consequences, but it would be as exaggerated to claim that simulation-based science is all about playing with visualizations of extreme events as it would be to claim that simulation codes are simply advanced calculators governed exclusively by the search for logic and truth. Modern as well as postmodern features are exhibited in the situated character of numerical simulation practices. The primary value of the present analysis is the questions it raises regarding how to explore numerical simulations further, especially in terms of differences between disciplines.

The different ways in which astrophysicists express critique of and resistance towards current black-box usage of simulation codes and (too much) belief in beautiful visualizations indicate that simulation in astrophysics is in a different phase compared to meteorology, especially considering the use of simulation output in the latter discipline. This usage is interesting to look closer into from at least three different angles. First, if output has become completely free floating from its original source of production, does this mean that the credibility of simulation codes is taken for granted (cf. Lahsen, 2005)? What does this imply about the position of numerical simulation in scientific knowledge production? Second, how do current socialization paths affect career patterns, skill and division of labor in simulation-based meteorological research? For example, how will doctoral students who only learn how to analyze (evaluate) output justify their expertise later on (cf. Ribes & Finholt, 2009: 384)? Finally, and related to the two preceding points, is the question of what are the consequences of this data usage regarding the hierarchy and status of different activities and tasks.

Whereas discussions of "simulations" and virtual worlds in a wider sense tend to focus on popular culture and leisure (Cubitt, 2001: 130), Turkle (1995) contextualizes scientific practice in social theory and Helmreich (1998: chap. 2) successfully describes how of the scientists working with Artificial Life simulations draw upon popular cultural resources. If and how this happens in meteorology and astrophysics would be interesting to analyze in order to deepen some of the issues that have only been briefly touched upon in the present paper. For example, an extended analysis of the connections between evaluation and entertainment is interesting in relation to how visual expressions possibly affect evaluations of scientific quality in relation to funders (cf. Turkle, 2009: 78) as well as peers (cf. Heymann, 2006) and if a culture of simulation is therefore more evident in re-presentative activities at the front stage.

Appendix A. Primary material

A.1. Observations

Summerschool on Multiscale Modeling and Simulation in Science, June 4–15, 2007, Bosön, Stockholm.

A.1.1. Astrophysics

Meeting A1: Symposium on New Trends in Radiation Hydrodynamics, Nordic Institute for Theoretical Physics, Stockholm, May 9–11, 2007
Meeting A2: Pencil Code User Meeting, Nordic Institute for Theoretical Physics, Stockholm, August 14–17, 2007
Meeting A3: Pencil Code User Meeting, Sterrewacht, Leiden, August 19–22, 2008
Meeting A4: Pencil Code User Meeting, Max Planck Institute for Astronomy, Heidelberg, August 24–28, 2009
Departmental Colloquium A1, Department of Physics and Astronomy, Uppsala University, January 25, 2007
Departmental Colloquium A2, Department of Astronomy, Stockholm University, January 26, 2007
Departmental Colloquium A3, Department of Astronomy, Stockholm University, February 2, 2007
Departmental Colloquium A4, Department of Astronomy, Stockholm University, February 16, 2007
Departmental Colloquium A5, Department of Astronomy, Stockholm University, February 23, 2007
Departmental Colloquium A6, Department of Astronomy, Stockholm University, October 5, 2007
Departmental Colloquium A7, Department of Astronomy, Stockholm University, November 9, 2007
Ph.D. Defence A1, Department of Astronomy, Stockholm University, December 15, 2008
Ph.D. Defence A2, Department of Physics and Astronomy, Uppsala University, April 29, 2009

A.1.2. Meteorology

Meeting M1, Symposium on Boundary Layers and Turbulence, Stockholm University, June 9–13, 2008
Meeting M2, Workshop within GEWEX Atmospheric Boundary Layer Study, Stockholm University, June 19–21, 2007
Meeting M3, Regional-scale *Climate Modeling* Workshop, *Lund University*, May 4–8, 2009
Departmental Colloquium M1, Department of Meteorology, Stockholm University, October 18, 2007
Departmental Colloquium M2, Department of Meteorology, Stockholm University, January 16
Departmental Colloquium M3, Department of Meteorology, Stockholm University, January 21, 2008
Departmental Colloquium M4, Department of Meteorology, Stockholm University, February 14, 2008
Departmental Colloquium M5, Department of Meteorology, Stockholm University, February 28, 2008
Departmental Colloquium M6, Department of Meteorology, Stockholm University, April 15, 2008
Ph.D. Defence M1, Department of Meteorology, Stockholm University, April 25, 2008
Ph.D. Defence M2, Department of Meteorology, Stockholm University, May 28, 2009
Ph.D. Defence M3, Department of Meteorology, Stockholm University, September 23, 2009

A.2. Interviews

A.2.1. Astrophysics

Interview A1, Physics Department, Stockholm University, November 23, 2006
Interview A2, Department of Physics and Astronomy, Uppsala University, December 20, 2006
Interview A3, Department of Physics and Astronomy, Uppsala University, January 9, 2007
Interview A4, Nordic Institute for Theoretical Physics, Stockholm, January 10, 2007

Interview A5, Department of Physics and Astronomy, Uppsala University, January 16, 2007
Interview A6, Department of Physics and Astronomy, Uppsala University, January 30, 2007
Interview A7, Department of Astronomy, Stockholm University, February 5, 2007
Interview A8, Nordic Institute for Theoretical Physics, Stockholm, February 7, 2007
Interview A9, Department of Astronomy, Stockholm University, October 4, 2007
Interview A10, Niels Bohr Institute, Copenhagen, February 21, 2008
Interview A11, Niels Bohr Institute, Copenhagen, February 21, 2008
Interview A12, Niels Bohr Institute, Copenhagen, February 22, 2008

A.2.2. Meteorology

Interview M1, Department of Meteorology, Stockholm University, October 11, 2007
Interview M2, Department of Meteorology, Stockholm University, November 8, 2007
Interview M3, Swedish Meteorological Institute, November 29, 2007
Interview M4, Department of Meteorology, Stockholm University, February 15, 2008
Interview M5, Department of Meteorology, Stockholm University, May 13, 2008
Interview M6, Department of Geosciences, University of Oslo, May 22, 2008
Interview M7, Meteorology and Air Quality Group, Wageningen University, June 18, 2008 (the interview was conducted in Stockholm)
Interview M8, Swedish Meteorological Institute, July 8, 2009

A.3. Webpages

http://astro-sim.org/content/view/15/29/, 09/18/2009
http://cmip-pcmdi.llnl.gov/, 05/26/2010
http://www-pcmdi.llnl.gov/ipcc/subproject_publications.php, 05/26/2010
http://www.mpa-garching.mpg.de/millennium/#VISUAL_MATERIAL, 09/24/2009
http://www.virgo.dur.ac.uk/, 09/24/2009

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