Data, models and Earth history in deep convolution. Paleoclimate simulation experiments and their epistemological unrest

Christoph Rosol

appeared in:

Berichte zur Wissenschaftsgeschichte 40 (2017), pp. 120 – 139

Abstract

Climate and Earth system models are not only used to project future conditions but also to reconstruct past climatic events. This is the second in a series of papers[1] that argue that paleoclimatology, the study of climate prior to the period of direct, instrumental measurements, is an epistemically radical field, one which directly abolishes the distinction between data and model, and reconfigures the notion of experiment. In doing so our notion of deep (or geological) and shallow (or historical) time has become convoluted. The present paper shows, first, how the introduction of general circulation models not only shifted the analysis of the complex causes and processes of ancient climatic change toward numerical simulation techniques, but also how this very introduction was accompanied, if not also fundamentally impacted upon, by paleoclimatic questions in the first place. Secondly, these computer experiments, and the temporal processes and scales they make operative, turn out to be a potent catalyst in bringing about a new sense of the temporality in which our present transition into the Anthropocene unfolds. By discussing the historical development of paleoclimate modelling, and through examining the productive heuristic qualities of its practices, this paper introduces the unconventional and pragmatic episteme by which paleoclimate simulation challenges our fixation with the category of uncertainty.

Abtstract, dt.

Klima- und Erdsystemmodelle werden nicht nur verwendet, um künftige klimatische Bedingungen zu prognostizieren, sondern auch um vergangene Klimaereignisse zu rekonstruieren. Dieser Beitrag ist der zweite in einer Reihe, welche die Paläoklimatologie – die Wissenschaft der Klimate vor Anbeginn direkter, instrumentenbasierter Messungen – als eine epistemisch radikale Praxis vorstellt, die in direkter und offener Weise die

Unterscheidung zwischen Daten und Modell aufhebt sowie den Begriff des Experiments rekonfiguriert und im Zuge dessen unsere Vorstellungen einer tiefen, d.h. geologischen, und einer flachen, d.h. historischen Zeit miteinander vermengt. Der vorliegende Artikel zeigt erstens, wie sich im Zuge der Einführung von General Circulation Models nicht nur die Wissensproduktion über die komplexen Ursachen und Abläufe früherer Klimawandel-Ereignisse auf numerische Simulationen verlagerte sondern diese Einführung selbst von paläoklimatologischen Fragen begleitet wenn nicht gar eminent beeinflusst wurde. Zweitens erweisen sich die numerischen Experimente inzwischen als potente Katalysatoren eines neuen Verständnisses für die spezifische Zeitlichkeit, in der sich unsere Gegenwart im Übergang zum Anthropozän entfaltet. In der Diskussion der historischen Entwicklung der Paläoklimamodellierung und durch die Untersuchung der produktiven heuristischen Eigenschaften ihrer Praxis stellt der Artikel unsere Fixierung auf die Kategorie der Unsicherheit infrage.

Keywords: paleoclimatology, modelling, general circulation models, proxy data, simulation, climate change, uncertainty, Anthropocene

Schlüsselwörter: Paläoklimatologie, Modellierung, General Circulation Models, Proxydaten, Simulation, Klimawandel, Unsicherheit, Anthropozän

1. Introduction

Paleoclimate modelling is a peculiar scientific practice. The numerical study of past climates bears a whole range of traits that touch on fundamental epistemological issues. Simulating ancient climates provocatively, but also, as I will show, productively plays with the dissolution of the classical distinctions between *observation* or *data*, the supposedly given and evident, and *theory* or *model*, the supposedly reductionist framework in which this data operates. In fact, paleoclimatology creates its own form of experimental interoperability between these two.

"Data describe, models explain," is a standard distinction by which paleoclimatologists, and climatologists more generally, understand the complementary role of data and model.[2] Whilst traditionally the collection of paleoclimate data seems to belong to the realm of the empirical, and hence "inexact" sciences such as paleobotany or geology, the modelling of the dynamics of paleoclimates pertains to the exact mathematical sciences, in the sense that it deals with quantities in a lawful manner. Yet with these numbers it professionalises procedures of speculation, tailors approximate methods and cultivates informed strategies of guesswork. The primary reason for this ambiguity stems from the fact that the data basis of paleoclimatology is generally thin, which shatters several barriers of certainty at once, especially once we enter actual deep-time domains, which make up 99.9% of Earth's history before the Quaternary period (our current period, consisting of the last 2.5 million years annum/Ma). The future—the holy grail of any climate simulation effort—is, of course, the realm of uncertainty par excellence. But the past, especially the deep past, is also highly uncertain. This is because the climatic record stored in terrestrial and marine archives; in stone, ocean sediment, and ice is extremely perturbed. Convoluted, dissolved and written over many times the 'book of nature" appears to be more like a palimpsest.

However, the reservoir of paleoclimatic knowledge is more important than ever and paleoclimate modelling has become a timely endeavour. In light of the current transition into the Anthropocene, the newly proposed geological epoch dominated by the system-wide effects humans and their technologies have on the fundamental biophysical, geochemical and climatic conditions of the Earth, everything that was formerly deep time becomes relevant to our own shallow time. Irrespective of the exact climatic state our Earth will lurch into in the coming decades and centuries, the last time Earth experienced anything close to the coming greenhouse age was in periods before the Quaternary. In entering such geohistorical realms, our present is put into its proper perspective and finding suitable analogues to former periods of rapid climatic change is seen as a vital guide to our imminent planetary future.

In order to find a natural equivalent to the "current grand climate experiment,"[3] or just to uncover the actual process behind any climatic event or interval that has happened in the past, simulation experiments are an indispensable tool. They help to discern causes and sequences of changes, whether abrupt or gradual; they are a means to test hypotheses and demonstrate analogies between periods of rapid or even catastrophic shifts in the past and present climate. Moreover, they integrate the vastly different time scales and temporalities within which climate and associated environmental changes take place, from the slow time regimes of deep-ocean turnover to the daily fluctuations of the atmosphere.

This paper introduces numerical experiments on paleoclimates as an epistemically radical field that challenges two first-rank dichotomies: data vs. model and distant Earth time vs. proximal history time. At its centre stands a historical account of how dynamical modelling has entered the analysis of paleoclimates, a practice that used to be almost purely empirical. Subsequently I will give some indications on how paleomodelling itself modifies our sense of the time we are in and the temporalities we shape. I have written on the subject of Anthropocene analogues and the notion of experiment elsewhere,[4] wherein I concentrated on the data aspect in the history of paleoclimatology. Hence, this paper and the present one are intended to complement one another.

2. *Paleodata is a "proxymoron"*

In order to reconstruct ancient climatic changes paleoclimatologists have to invert the perspective of climatologists. Rather than looking up into the fluid medium of climate, the atmosphere, they go down into the lithosphere strata (which itself is a fluid of sorts flowing viscously at a very slow pace). Instead of directly measuring variables such as temperature, humidity, or wind speed they infer climatic variables from proxy indicators that carry a "record" in terms of the geochemical, biological or physical signature of environmental responses to climatic factors. These climatic indicators usually consist of very subtle differences, measurable only with high-precision instruments. In addition, their general scarcity, makes these indicators a precious "data of opportunity," especially as one proceeds to older geological periods.[5] Accordingly, many curious "methods of vicariousness," as they could be called, have been devised. Amongst them are the measurement of trace gases, trapped in air bubbles in ice cores or certain isotopic ratios in deposited calcite shells from marine microorganisms, the mapping of paleontological assemblages in rocks or fossil pollen in lake sediments, the width of tree rings or respiratory openings in fossilised plant leaves. Curiously enough, these biological indicators are also referred to as "paleo-environmental sensors"[6] or "climate witnesses":[7] long-dead organisms that acted as precision instruments, detecting, recording, storing and documenting the very climatic conditions of their own lifetime. In lieu of electronic devices transforming the physical into the symbolic, paleoclimatologists rely on a more original source of environmental sensing: life itself.

Hence, this change in the materiality of the record is, first of all, a profound change in the medium in which climatic information resides. Direct measurements of climatic variables are being replaced by biogeochemical inferences taken from fossilised matter. As the data source shifts from historical to prehistorical time or from "paper authority" to the "natural archive," this not only results in the separation of scholarly expertise, creating a division between paleoclimatology and historical climatology, it also mobilises new practices and ways of thinking about what empirical data, instrumentation and observation means.

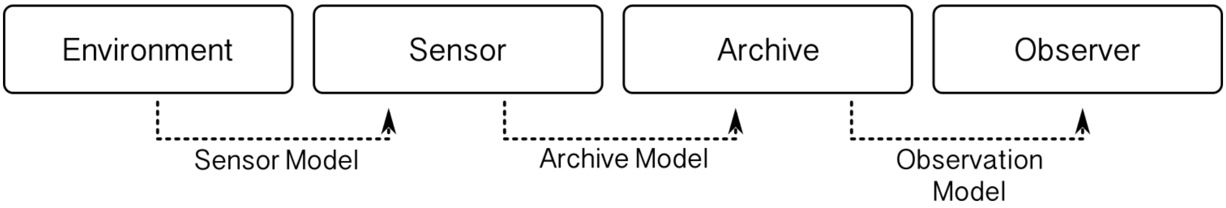
As the famous quip goes: "Raw data is an oxymoron."[8] But proxy data does not even pretend to be raw. From the perspective of paleoclimatology, observational data is the result of a long chain of technical transformation processes that translate physical or chemical traces found in rock, ice, or ooze recovered from lakes or seabeds into proxy data and then climate data. This encompasses a complex passage through a patchwork of media and instruments, including sophisticated procedures of model-based calculations, dates, references, interpolations and calibrations. In the case of geochemical measurements of marine sediments—the geoarchive and method of choice for climates older than 1 Ma or so—this passage entails not only a geotechnical infrastructure for recovering and storing sediment cores, including drilling vessels, hole re-entry cones, core repositories and standardized reference material. But also assembles a range of central elements of technical media such as is found in a mass spectrometer, including lenses, apertures, circuits, processors, screens, et cetera. It is one thing to replace a thermometer with a mass spectrometer that derives paleotemperatures from the ratio of the oxygen isotopes ^{18}O to ^{16}O in calcite shells. It is another thing to actually calibrate and interpret such a proxy value through a whole set of highly technical modelling capabilities.

In his ethnographic study on the work performed in a paleoclimate research laboratory, Willem Schinkel has shown how "comparability devices" such as isotopic ratios and further "comparability techniques" engender a fixed set of quantitative relations between proxies and the climatic values they stand in for and through that make climates themselves comparable.[9]

He argues that only through an intricate arrangement of established commensurability and difference control is possible, thereby "cordoning off a comparity space"[10] from which climates can be rendered changing across time scales.
While Schinkel convincingly drafts a general analytical vocabulary to foreground the ways in which contemporary empirical paleoclimatology "makes things comparable" he fails to discuss the crucial role that models play in his rendition of the act of proxy-making. To continue with the example just given, geochemical measurements are checked and validated through a variety of modelling techniques: age models help dating the sample by determining a coherent chronology, geophysical models help to reconstruct the tectonic configurations and the movement of the original sedimentary deposits, other models separate the signal from biological and geochemical side-effects of the isotopic fractionation process itself. There is a tremendous number of algorithms at work in the making of a paleoclimatic value.

But once derived, the travel of that value through the data/model architecture of modern paleoclimatology just only begins. Since proxies are highly site-specific and usually only record the local weather at a certain point in time, a single quantity does not say anything about climate. Instead, it has to be statistically assimilated and homogenised with as many available data points as possible and it also has to be aggregated with as many other proxy sources as possible. Only a multi-proxy approach provides sufficient confidence in the data set to state reliable values for ancient sea surface temperature, the extent of sea ice during the last glaciation, et cetera. The day-to-day practices of empirical paleoclimatology therefore lie in large mapping efforts that require the compilation, coordination, and transformation of large amounts of highly varied paleoenvironmental data (and its metadata) with the help of sophisticated data management and retrieval systems.[11] There is no data without a data model.

Moreover, the further back in time you go, the more there is an apparent radicalisation and escalation of the proxy principle to be asserted. Not only does the resolution get coarser and the proxy information noisier, the whole "environmental sensorium" itself becomes progressively more indirect and subject to modelling itself. Being only third or fourth order "witnesses", deep-time proxy data is even more explicitly modelled than, for example, the re-analysed climate data of the historical period that historian of science and infrastructure Paul Edwards discusses in his book *A Vast Machine*.[12] In fact, he suggests there are "models that explicitly simulate the sensor [...] either in 'forward' mode driven by outputs from a climate model or in 'inverse' mode to reconstruct more traditional climate variables so that they are consistent with observations."[13] The increasing use of the forward mode, which directly simulates the evolution of proxy variables within a climate modelling framework, based on physical and biological principles, requires an increasing generated rather than empirical data. A whole system of transformations and back-transformations of modelled and observed data in conjunction with a mechanistic model how the environment affects the sensor, the sensor affects the archive and the archive affects observation is nowadays necessary to appraise the interpretative quality of the entire "proxy system."[14]



Caption: A conceptual model of the sequence of technical transformations within an entire proxy system (adapted from Evans et al., 2013)[15]

For any advocate of the classical (and still widely persisting) "Mode-1" view of science, in which it is believed sound knowledge production is based on a methodically strict and disciplinary closed framework,[16] such a practice would certainly amount to a moderate representation crisis. Yet, there is more humiliation in stock. The liberation process of data from its original meaning as "the given" does not stop here. Even when all paleo-data diagnostics and syntheses are made, the "empirical" quantities are still not fixed. Instead they are kept in endless suspense during their actual use: paleosimulation experiments.

3. Comparing climates

Classically, the observational data would be there to constrain the simulation experiments. But with paleodata reconstructions it actually works both ways: model and data inform each other in an iterative and open-ended process, "whereby one discipline can be used to test the other."[17] While the data presents the boundary conditions for simulation runs, the output of these experiments itself helps to reinterpret the data. Thus, "model-data comparison" is one of the central practices of current paleoclimatology and further "marrying the signal from computer models and biological proxies" is a mandated future.[18]

The primary means for such model runs are General Circulation Models or GCMs, the prominent three-dimensional model class that originated from numerical weather prediction models and which resolve the thermo- and hydrodynamical evolution of atmospheric dynamics. Briefly summarised, today these models have expanded towards fully coupled atmosphere-ocean models (AOGCM) and increasingly incorporate features such as dynamical vegetation or an interactive carbon cycle, in which case one generally speaks of Earth System Models, ESM. Due to their high computational demand GCMs were, until quite recently, not well suited for the exceptionally long (thousand year) simulations of actual paleoclimate experiments. Accordingly, many of the earlier quantitative modelling attempts were made with more conceptual model designs like Energy Balance Models, Statistical-Dynamical Models, or low order Paleoclimate Dynamical Models.[19] However, with increasing computer power, one can delineate a general tendency to join up to the prognostic capabilities of GCMs. Over the last two decades or so, the modelling community put much effort in developing a hybrid model architecture that combines elements of simple Earth Balance Models with GCMs. At the expense of a coarser spatial and temporal resolution, what are called Earth Models of Intermediate Complexity (EMICs) permit long integration times and the coupling of more physical processes. It can be anticipated that, wherever computational abilities are in place, the better resolved and more explicit simulation of climate features in comprehensive ESMs will overtake EMICs in paleoclimate modelling studies.

Yet, rather than merely repeating the usual history-folklore of any computational science, that is, its historical evolution from simple to complex models, in practice, the example of GCMs is less straightforward. GCMs have, from the very beginning on, presented a vital stimulus to the establishment of the data-model bind of paleoclimate reconstructions. The idea of the “infinite forecast” already stood at the creation of numerical climate modelling in the mid-1950s at the Meteorological Computing Project based at Princeton’s Institute for Advanced Study (IAS).[20] This infinite forecast was not a forecast in the usual sense but rather a study of the statistical features of the general circulation in which the short-term hydro- and thermodynamical problem of weather prediction was replaced by the equilibrated pattern of global atmospheric flows. Integrating the dynamical equations over long time intervals necessarily leads the problem away from a consideration of the initial conditions so prevalent in numerical weather prediction, to the boundary conditions; that is, in essence, from weather data to climate data. Reproducing the statistical general circulation pattern results in setting aside variables such as air pressure or wind speed at a certain point in space and time and instead factoring in long-term features such as insolation, orbital parameters, the specific configuration of sea, land and mountains, the presence of sea ice, chemical composition of the atmosphere, heat budget of the ocean, et cetera. Changing any of the boundary conditions would lead to different circulation patterns—an experimental test arrangement perfectly suited for studying both alternate and changing climates. Or, as the meteorologist Richard L. Pfeffer remarked at a seminal conference held at the IAS in 1955:

> "Experiments of this sort would serve as building blocks toward a theory of the general circulation and climatic change. The success or failure of such work will not necessarily be measured by the extent to which the model succeeds in predicting the actual development of the atmosphere following the initial state, but by the extent to which the solutions lead to a better understanding of the effects of different external parameters on the general circulation."[21]

The conference took place in the wake of Norman Phillips' first numerical experiment on the general circulation.[22] Phillips was a member of the Meteorological Computing Project team at Princeton. His experiment simulated hemispheric motion over an integration time of approximately one month, after which the calculations broke down. Nevertheless, the simulation managed to equilibrate on the more or less familiar patterns of the general circulation. The purpose of the IAS conference was to convene an informal "Study Group on the General Circulation of the Atmosphere" (the original title of the meeting), with the purpose to discuss the problems involved by the utilisation of numerical integration techniques for studying the features of global atmospheric behaviour. However, there was more: they also stated that "This research is in the nature of a break-through and seems to justify an expanded effort to study not only the zonal circulation but also climatic anomalies".[23] Phillips' study is now considered to be the first climate simulation since it made clear the applicability of these kinds of experiments for the simulation of different climates. Accordingly, the Princeton meeting turned into an impromptu climate study group considering not only the possibility of an "infinite forecast" but actual climatic change across different time periods. After the head of the Special Scientific Services Division at the Weather Bureau, Harry Wexler, presented his talk on "Possible causes of climatic fluctuations" the discussion went on over "the recent warming trend." Wexler stated:

> "Von Neumann pointed out that the warming trend during the last 50 years is a comparatively small effect. A larger effect which has thus far not been explained is the distribution of ice during the glacial ages of the pleistocene epoch [...] Von Neumann called for a quantitative physical attack on questions of this nature."[24]

What mathematician John von Neumann meant becomes clear when looking into his published talk, where he states that no “dialectical method”, that is, qualitative reasoning, would provide adequate answers to reconstructing the origins for certain ancient climates, since many, even contradictory causes might lead to one and the same effect. Only quantitative attacks in the form of long-range numerical experiments, however difficult, might yield possible explanations, he posited.[25] Von Neumann’s example was the conflicting views taken on “whether the ice age was due to the fact that the sun became hotter, or that the sun became cooler”. All arguments for and against each hypothesis were based on aligning physical theory with empirical evidence. But how can an observed effect be linked to a physical cause, when so many factors are in play in the configuration of a certain climate and, all the more, when a turbulent hydro- and thermodynamical system such as the atmosphere intermediates between all of these?

Arguably, von Neumann’s understanding of the general subject of paleoclimates had been heavily informed by discussions he shared with Wexler, who had an interest in climatic changes since at least the 1940s, oscillating between explanations either based on the effects of volcanic eruptions or that of solar variation. In one of their frequent letters, dated 19 May 1955, von Neumann praises Wexler’s attempt to “visualize different factors to be operative” in climate variations, together with his: analysis showing how contrasting patterns of climate can arise side by side even if [only] one factor is assumed.” He concludes: “In view of the great complexity of character of the different phases of climatic history as reported by Brooks, Willett and others, there is much to commend your approach.”[26]

Now with this new tool of the electronic computer it seemed futile to switch into forward mode: testing an hypothesis by running a numerical experiment on how any one factor (such as changing insolation or volcanic outbreaks) would affect the general circulation model. For von Neumann there was a natural extension of the programmatic design of numerical weather prediction to “forecasting” climatic fluctuations, if only this meant scaling between time categories governed by initial and by boundary conditions.[27]

From the perspective of the emerging climate modelling community (which was more or less in full attendance at the Princeton conference) climate *is* the general circulation and climatic change its evolution over time. From the perspective of the (paleo)climatologist, such a conclusion was met with more scepticism, even years after. Returning from a NATO-sponsored conference in January 1963, Hubert H. Lamb pondered several ways in which the theoretical “meteorologist” and his study of the “meandering of the circulation of atmosphere and oceans” might contribute to the effort of the climatological “empiricist”, to which he certainly regarded himself. He concludes that the simple equation of climatic variation with a changing general circulation “must [...] have seemed to many too bold a claim. [...] It doubtless partly represents the physicist’s hope that he has an experiment in which other things remain equal.”[28] Lamb’s accusation of reductionism is both unfounded and true, as we have just seen in von Neumann’s assertion of the complexity of climatic controls and his trust in finding solution and salvation in dynamical modelling. The “data-guy”, Lamb, remained a fierce opponent to a predominance of modelling throughout his career, instead devoting all his efforts to obtaining estimates for, calculating and mapping the large-scale atmospheric circulations, from paleobotanical and oceanographic evidence to historical records.[29]

A more constructive view was held by another climatologist and colleague of Wexler; J. Murray Mitchell, who realized that physically informed paleoclimatology was a tremendous opportunity “to piece together the paleoclimatic drama.”[30] As he noted, while the climatologist is fascinated by the “remarkable variations of climate” that have left their “subtle imprints in the Earth [...]. His larger ambition is of course to make meteorological sense of the paleoclimatic record as a whole, particularly as regards physical cause and effect.” Fortunately, he believed this was now conceivable “by some important developments in meteorological theory.”

> “Already, today, the atmospheric scientist is finding it possible to construct remarkably realistic mathematical models of the atmosphere (e.g. Smagorinsky, 1963), by which he can explore the nature and extent of various subtle forms of dynamical unrest that underlie the perpetual evolution of climate and circulation from one pattern to another. Indeed, he is now standing at the threshold of a new era in which, for the first time, he will be able to derive quantitative evaluations of a number of hypotheses of climatic change by means of suitable controlled experiments with these mathematical stand-ins for the real atmosphere.”[31]

A general atmosphere of departure is tangible in these words and they were shared by other open-minded figures working at the boundary between meteorology and climatology, figures like Hermann Flohn. Flohn was an ardent follower of the developments of dynamic meteorology and had a long-standing interest in both the nature of the general circulation and geological and paleoclimatic questions.[32] Now, with upper air soundings, satellites, and electronic computers available, a new understanding of the physical processes at the synoptic scale and the anomalies they exhibit, was possible. These understandings were a necessary precondition for evaluating both past and current climatic change.[33] Model simulations, but also material laboratory experiments such as the “dishpan” studies performed by Dave Fultz at the University of Chicago, in which dense liquids were rotated in hemispheric shells or other mechanical apparatuses, were vital to consider the "dependency of circulation types from geophysical parameters that allow an interpretation of paleoclimatic problems" with "model calculations going substantially further ... in showing the possibilities, in principle, to advance on quantitative solutions of paleoclimatic problems through theoretical climatology."[34]

Paleoclimatological knowledge could now be stated in dynamical terms while the capability of dynamical models could be tested against available paleodata. Since the records from the Quaternary were relatively well preserved, dense and available in high resolution, focusing on the ice ages was a natural experimental field for the first actual paleosimulations that started in the mid 1970s.[35] Yet the the use of ice ages had another reason: they gave the opportunity to model a highly contrasting climate compared to today in which the signal was large enough to fall outside the normal error envelope of both model and data and, through this, would allow for robust comparisons. Or, as climate modelling pioneer Syukuro Manabe told an interviewer, when asked whether he preferred "paleo-planet models [...] or long model integrations": "climate [history] has always fascinated me because the changes are so large. And so that, enabled [you] to hit your model by hammer, rather than tinkering with small changes. So, we did that in changing CO_2, halving the CO_2, or something drastic we'd do."[36]

This quote shows the intricate relationship, if not identity, between the first paleoclimate simulations and what has been the reference experiment of climate modelling since Manabe and Richard Weatherald did a first GCM run to test the response of the climate system to a doubling of CO_2.[37] Paleoclimatic modelling had also started out with such equilibrium sensitivity experiments, exercises to compare the differences in equilibria of certain "snapshots" in climate history against a control run of the current or pre-industrial climate. In the 1970s this snapshot consisted in the Last Glacial Maximum, about 18-21.000 years before present (BP), the biggest contrast (or "hammer") to current climate. Later on, other periods were added, namely the mid-Holocene Warm period (6000 a BP) and the last millennium. In the early 1990's this practice got globally coordinated through the Paleoclimate Modelling Intercomparison Project (PMIP) which is currently in its fourth phase and has now added the mid-Pliocene warm period (3.2 Ma ago) to the carousel.[38] Such snapshot exercises are a somewhat natural standard for GCM simulations, because this is basically what GCMs do: spinning up the model with a chosen parameter set, and watching what the result is after the modelled climate has settled into equilibrium. Moreover, the practice of running GCMs with the boundary conditions of an ice age or exceptionally warm periods also helps to compare and calibrate the models themselves, and has therefore played a crucial role ever since the 1970s in evaluating models' predictive capacity. It is the validation of the GCMs itself that presents the main reason for undertaking paleoclimate experiments.

4. Modelling the "paleoclimatic drama"

But what about climate *changes* instead of just climate *differences*? Snapshot experiments were performed without concern for the *path* leading to a certain equilibrium or from one equilibrium to another. Moreover, what if equilibria do not even exist, as Barry Saltzman succinctly suggested in a very instructive contribution in 1985: "it is unlikely that at any particular time the system will actually be a realization of [an] equilibrium state, even if the equilibrium is stable. This will be true if only due to the ubiquitous presence of noise generated by higher frequency phenomena that cannot be accounted for in the model"[39]—higher frequency phenomena, of course, referring here to the rapid fluctuations of atmospheric conditions or, in other words, the weather.

Accordingly, the crucial aspect of the causes leading to the *onsets* and *terminations* of glaciations gradually came into focus once the first generation of sensitivity experiments was performed. It was known that the cyclical succession of glaciated and deglaciated intervals were mainly the result of changes in the orbital parameters of the Earth (the famous Milankovitch cycles[40]). But the relatively minor changes did not provide an explanation for the full scope of the drastic climate swings of the Pleistocene. Climate models provided a further incentive to experimentally study the processes that magnified small initial variations and were able to tip the climate system either into a cold or a warm state.

That the physical system of climate might be able to amplify a modest initial impulse was considered on theoretical grounds since Edward Lorenz applied his insights about the instability of atmospheric flow to the climate problem.[41]

> "The intriguing thing that is suggested by Lorenz's analysis is that, under certain conditions that may have been met during the Quaternary, relatively minor and transitory environmental disturbances may have sufficed to „flip" the atmospheric circulation and climate from one state to another, and to „flop" it back again."[42]

Through a theoretical treatment of the highly non-linear form of the equations governing atmospheric dynamics and through tinkering with GCMs it became apparent that the general circulation, and thus: climate, exhibited statistically unstable behaviour. But such "autovariation" of the atmosphere alone, in which fluctuation is produced internally, would decay within a few weeks as the atmosphere is also a dissipative system. However, the climate includes much more inertial subsystems with much longer "internal memory" such as the ocean or the cryosphere. Perturbations affecting the slow thermohaline circulation or the build-up or collapse of ice sheets would yield variation on a much bigger time scale. Formulated in the ICT-informed language of climate science these subsystems exhibit divergent "response times" (also called "equilibration," "relaxation," or "adjustment" times): a measure of the time it takes for the system or subsystem to re-equilibrate after a small forcing.

> "In view of many processes that serve to relate one portion of the climate system to another, and the disparate response times of the system's atmospheric, oceanic, cryospheric, land surface and biomass components ..., the history of the Earth's climate can be expected to show variations over a wide range of time scales. Even if the external factors causing climate change were concentrated in well-defined frequencies, the high degree of coupling or interaction among internal processes in the climate system would be sufficient to create a virtually continuous spectrum of climatic variation. It is precisely these nonlinear feedback processes, [...] that make the analysis of climate and climate change a difficult if not impossible task without the assistance of models. (As we shall see, however, even with models there remain significant uncertainties, although the process is now at least a systematic one.)"[43]

What is called upon as a necessary, albeit imperfect, tool to tackle the nonlinear feedback processes and many time scales on which changes are taking place is, first of all, a theoretical result of the modelling practice itself. In 1984, based on the analysis of ice cores, glaciologist Hans Oeschger proposed that the climate system of the glacial-interglacial periods indeed may have operated like an electronic switch,[44] this came only *after* the physical theory was long established. The high-resolution readings from ice cores showed that the evolution of the climate system may indeed be subject to abrupt changes and spontaneous jumps. Empirical data, if not vindicated at least reinforced mathematical theory already elaborated on some 20 years earlier. Now it became standard to formulate the climate in 'system-dynamical' terms, in which the evolution of the system can be subject to bifurcations, directing either into this or that possible attractor state and that the large fluctuations of glacial-interglacials are indicative of bimodal systems at a critical point.[45]

Climate is precisely not time-independent but is instead the result of processes happening on different time scales, all at the same time and with non-linear interactions between the system components leading to many sources of instabilities. Even more crucially: the actual state of the dynamic system depends on its own history, a function called hysteresis. Any climatic event is to a high degree a result of the dynamical memory of the chaotic system. That means that even if modelling paleoclimates as a physical system bears a certain *ahistorical* logic in its description of actual empirical events—both physics and algorithms do not care about the actual period to which they are applied to—it also supports the idea of a time-dependent “narrative” leading to these events. Simulated climatic events of the past follow a peculiar structural temporality. They are not embedded into the larger chronological evolution of climate but focus on an encapsulated but hysteretic process: a self-contained drama of which the climax is preceded by a specific exposition and leading to catastrophe and a state of new equilibrium. Which brings me to my final point, which is less technical and more theoretical, perhaps even philosophical, and which might need a longer explanation.

5. *Deep time, our time*

It is one thing to advance the understanding of the entire physical system of climate by simulating ice age swings. It is another to understand current anthropogenic climate change. The simulation of episodes like the Dansgaard/Oeschger events or the comparison of the Last Glacial Maximum with the last millennium does not explain the process of and environmental response to a rapid release of greenhouse gases. Concentrating solely on CO_2 and its equivalents, Hermann Flohn already asked in 1979: “Can climate history repeat itself?” The question was merely rhetorical, he did not have an answer, but instead wanted to review the state of knowledge about four recent warm phases as possible “climate scenarios [...] of a future evolution”[46]: The Medieval warm period (900-1050 AD); the Holocene warm phase (6000 a BP), the Eemian interglacial (125.000 a BP) and the last period of an ice-free Arctic Ocean (12-2.5 Ma BP). Characteristically of both Flohn’s general attitude and the state of affairs more than twenty years after Phillip’s experiment, empirical and model results went hand in hand in his estimates.

Today, forty years after this pragmatism had prevailed, we know that in the search for a suitable geological analogue to the present or near future one has to look even further back into Earth history, way beyond the astronomically forced and well documented climate changes of the Quaternary and into climate transitions driven by strong CO_2 forcings. One would have to look beyond the Pliocene, about 5-3 Ma ago, and its atmospheric CO_2 concentration of 400 ppm—a level we have famously accomplished ourselves in 2014, and which may cause an eventual global temperature adjustment of 2-3 degrees centigrade above the present within about 40 years already. One would even have to go beyond the 17 Ma ago Miocene climatic optimum, of which global temperatures of 4-5°C we could reach within the next 100 years under an unrestricted emissions scenario. In fact, in our current 'business-as-usual' mode we are pushing, in the very long run, towards record highs of the last 40-50 Ma, well into the Eocene when a warm 'greenhouse' climate prevailed and alligators thrived far above the Arctic Circle.

Of course, blowing through past ages on a time machine while cruising forward through our impending future is scientifically not fully legitimate as I have just explained; since we are not dealing with a linear correspondence between carbon dioxide and temperature but a complex system including hysteresis. But in any case, the message is quite clear: At current emission rates we are steering the planet out of the period of the succession of glacials and interglacials and into 'greenhouse; conditions that last occured in pre-Quaternary times.

Paleoclimatologists thus end up comparing our current transition into the Anthropocene to something like the Paleocene-Eocene Thermal Maximum (PETM), dated at 54.8 Ma ago, when excessive amounts of methane and CO_2 escaped from the ocean floor at a pace that is equivalent to, or even exceeded by, the current anthropogenic rate of emission.[47] The effect, lasting for about 90, 000 years, was tremendous: the Paleocene-Eocene boundary is characterized by a large extinction of benthic organisms and an evolutionary turnover on land that allowed mammals become the dominant species. In fact, it was geologist Charles Lyell in the 1830s who christened the Eocene as "the dawn [eos] of the present state of the animate creation".[48]

Yet, almost two-hundred years and many computer model generations later it might be less appropriate to speak of the PETM in such an evolutionary, that is linearised (albeit discontinuous) fashion. Rather it seems appropriate to describe the PETM the way the geophysicist Richard Alley did in a presentation a few years ago, when he commented that "things get out of place and out of time as it were."[49] Being out of time, the PETM engages in temporal transgression: the 55 Ma ago catastrophic event might be more proximate to our current climatic turmoil than the mid-Holocene optimum, or even the last millennium for that matter.

I argue the very epistemic and temporal transgression of paleoclimate modeling, its *timelessness* or better *timefulness*, has much to do with this move. In reversal of the Lyellian principle of uniformitarianism, which is based on the tenet that "the present is the key to the past," paleoclimate modelling now offers a folded-in epistemic picture by narrating a "past [that] becomes the key to the future."[50] However, according to a recent modelling study, reviewing possible candidates for a geological analogue to our future, even the PETM cannot hold its promise, because, as a matter of principle, Earth history does not repeat itself and, consequentially, the Earth itself “fails to provide a true and direct analogue.”[51] Yet, the PETM still holds as the closest available comparison to our modern time, however radical in its appropriation of the proxy principle. Only detectable through sensitive high-tech geochemical measurements in extremely long sediment cores and adjusted with and by the technical assemblage described earlier and only reconstructed as a sequential “narrative” through experiments, the PETM as a factual figure is stripped of any clear certainty. Every hint of a proxy is a “datum of opportunity,” every model run a hypothesis. The search for deep-time paleoclimatic analogues probes evidence and experiment at their conceptual limits.

To adapt the title of a famous novel, the PETM thus seems “extremely noisy and incredibly close.” It is highly uncertain and cannot, as a matter of principle, be a true 1:1 comparison to our current situation. Nevertheless, it is an important and valid means to assess the impact of rapidly emitted greenhouse gases. The philosopher and science historian Michel Serres offers an intriguing method to think and to make peace with this dilemma, by considering it between what his student Bruno Latour has termed “matters of fact” and “matters of concern.”[52] Serres circumscribes this method as the method of Hermes, the god of transitions and boundaries. Hermes, he writes “exports and imports; thus, he traverses. He invents and can be mis- taken—because of analogies, which are dangerous and even forbidden—but we know no other route to invention.”[53]

This inventive traversing applies, first of all, to computer simulations. “The status of simulation is similar to the status of the experiment,” writes Michel Serres in his essay: “La simulation, technique nouvelle, ancienne tradition.”

> “Mathematics express the real, that is, everything that is possible, and experiments deliver profiles of a contingent world. Consequently, simulation, using virtual images, liberates the abstract from its kingdom to also provide us with such profiles. ... the status of simulation is similar to the status of the experiment.”[54]

Serres makes clear that simulation is not something new within the history of the sciences, but that it follows the very mode by which all sciences, the earth and life sciences in particular, have explored the complexity of this very world since ancient times. Moreover, what he realises is that the subtleness by which these sciences use their arsenal of mediate techniques provides for a “more sharing, open, connected way of knowing, in which he who knows participates in the things he knows.”[55] Climate modelling is participation in the world through an endless circulation of information and algorithms that heuristically resemble, even if by definition they never fully match, the endless circulation of energy and matter that constitute the Earth’s existence as a habitable planet. Or, put simply and less solemnly, such models are the best we have in order to understand, predict and retrodict the climate.

The traversing of Hermes, moreover, specifically applies to its autonomy of chronological, sequential time. “Every historical era is likewise multi-temporal, simultaneously drawing from the obsolete, the contemporary, and the futuristic,” explains Serres in a conversation with Latour,[56] going on to say: “An object, a circumstance, is thus polychronic, multi-temporal, and reveals a time that is gathered together, with multiple pleats.” What he describes here is a topological, pan-topic, or, more true to the subject, a turbulent model of a crumpled, folded time, by which temporally very distant instances close ranks while others, chronologically more proximal ones, are being separated. As much as algorithms do not care whether they are applied to either climatic forecasts or hindcasts, neither does Serres, in a timeless gesture of scholarly naivety,[57] limit himself to understanding time as being in a sequential, linear order.

In the Anthropocene, we see human and Earth history folding into a singular contemporaneity, and paleoclimate experiments are a potent catalyst for this temporal interlocking. We can now see a situation like the 54 million year ago PETM as something not separated from us, but instead we see its '*then*' folded into our own ‘*now*’. Given the modelling capabilities of the early twenty-first century, proxy signals from deep time can be more proximate to us than the direct noise created by the shallow temporality of yesterday’s news. A precise unfolding of the PETM is not and can never be a “matter of fact” but is, more than anything else, a :matter of concern.” That is a good enough reason to keep the paleomodelling community busy for quite some time.

6. Conclusion: Highly uncertain but certainly needed

“Data describe, models explain”. But as we have seen, the distinctiveness of this relationship is much less straightforward than the dictum assumes. In fact, the circumstance is acknowledged only a little later in the very same paper in which it was given as the opening statement: “The indeterminacy of the data and the present limitations of the models thus dictate a synergistic approach for understanding climate variations that relies on integrating paleodata with paleoclimate model simulations.”[58]

Moreover, the indeterminacy and limitations alluded to are, in fact, of a quasi-ontological nature.

> "The data record how climate has changed, but data alone cannot provide an unambiguous explanation of why a particular climate state occurred or changed. This situation arises because most climatic variations recorded geologically have multiple, hierarchical causes (e.g. there is more than one way to create drought in a region) and because environmental subsystems display generally nonlinear responses to climate. Consequently, multiple cause-and-effect pathways can produce the same response in a paleoclimatic indicator."[59]

Models step in to ameliorate the inextricable situation, to reduce ontological uncertainty. But then again, it is the models that are imperfect.

> "Models based on physical principles (or widely accepted empirical representations of those physical principles [that is: parametrizations, CR]) do have the potential to provide mechanistic explanations of past climatic variations, provided they are known to work, are applied in an appropriately designed experiment, and (perhaps most importantly) explicitly account for all of the components of the climate system that are involved in a particular climate change."[60]

In other words: they will never be perfect! Although the climate modelling community is quickly moving towards the establishment of more comprehensive Earth System Models it is irrefutable that any model will always remain incomplete and reductionist. Simply because it is a *model* rather than the target system itself. So, "piecing together the paleoclimatic drama" means doing it together, empiricist and modeller hand in hand, bit by bit, or byte by byte. As Peter Galison has already shown in a seminal paper twenty years ago, the "delocalized trading zone" of computer simulations, where "an intermediate language, a kind of formalized creole [...] understood both by theorists and by experimenters" has served as a "tertium quid" for all kinds of disciplines, practices and forms of knowledge from its very inception in the 1940s on.[61] This insight applies as much to the deployment of Monte Carlo methods to problems in particle physics, radiation diffusion or hydrodynamics—the case studied by Galison—as it does to climatology, and it's switching between the lab and the field, making both increasingly indistinguishable.[62] The "trading zone" has since become a zone of convergence, with nearly all sciences speaking the language of simulation. Computer and biological signals are married, data and model create a synergistic ensemble in which one does not hold up its integrity without the other. The data/model construct of paleoclimatology then seems to operate in an almost virtual environment, in which free-floating variables are always conditionally and kept in suspension.

But grant yourself a second thought before crying out that the emperor is naked. Does this insight, that paleodata and model are two-sided manifestations of the unknown knowns, which mutually generate and calibrate each other, really invalidate the whole endeavour of paleoclimate reconstruction? Does it become a mere technical construction divorced from reality?

Not so. As media scholar Claus Pias put it, it is particularly because of this ongoing iterative, always approximate and heuristic, half-empirical and half-physical strategy of running model experiments that a certain epistemic robustness is generated.[63] It is precisely because both data and model constitute an interactive and interconnected loop that they create conditions for temporal stabilisations within a field of knowledge that is, at its very epistemic core, and as a result of its subject, unstable. Climate is a free-wheeling and ephemeral beast, or, in the language of the climate sciences, it is characterized by internal instabilities, involving nonlinear interaction among different components of its system, which can occur even if there are no exogenous forces. Uncertainty is the very business of climate modelling.

"Every experiment is a process deeply marked by uncertainty. On the one hand, the possible is invited to occur. Somehow on the other hand, what is possible must already have been decided before,"[64] sociologist of science Helga Nowotny reminds us in her latest book. Contrary to the cries for expurgated and sterilised certainty, it is ambiguity, vagueness and the impermanence of knowledge that needs to be tolerated, if not even embraced, as productive epistemic categories. Improvisation and incrementally muddling through are sound strategies to cope with instability.[65]

Through allowing us to enter into the "twilight zone" or even "dark ages" of deep geological time, paleoexperiments are a radical but also very "honest" form of simulation. It openly acknowledges its opportunistic timbre, in which representation is not a meaningful category. Instead, highly vicarious traces in "paleo-environmental sensors" provide productive opportunities, within a neatly specified framework of multi-proxy and multi-model checking and validating. And given that computer simulations are, more generally

> "consciously—and as a matter of course—furnished with a hypothetical index, they admit to their fictional components, they position themselves within their conceptual frame of reference, they thematize their performance, they are aware of their problematic genesis, and they specify their limited application."[66]

The careful epistemic practice of paleoclimatology, together with its overly apparent scarce data basis are no exception to this self-reflexive configuration. As much as climate scientists "are clearly lucid and display epistemological maturity"[67], paleoclimate scientists have good reason to present this demeanour too. One can hardly find any paleoclimate study that gives an incontrovertible impression about its assumptions and its results.

Take, as contrast, the future. Although uncertain by virtue of definition, and with all the necessary caution applied, we seem to have at least some grasp on what the outcome of the "current grand climate experiment" could look like. That is to say, some confidence in the predictions is justified, not least because we sometimes feed reconstructions of previous climate changes into the scenarios. Future and past *inform* one and another here, informing in a material as well as an immaterial sense. In fact, paleoexperiments nourish a temporal configuration that involve multiple time horizons, employ heterogenous temporalities, and can catalyze a *pan-historic* transgression of past, present and future. Rather than following chronological proximities, they fold, by default, Earth history into similitudes and dissimilitudes. As much as computer simulation stands emblematic for the new time regime or "chronotope" of a "widened presence" that the "Eigenzeit" of digital computing, prediction, cybernetics and its technical conceptualisation of feedbacks, including the "media-technical feedback of past and future"[68], have brought, the simulation of paleoclimatic events is ultimately expanding this presence into one whole "timeless" or perpetual now.

Turning the argument upside down, we might also just ask how "certain" our knowledge of the present, the crisis-afflicted adolescence of the 21st century, is. As historical observers we cannot even agree on the 0.00000001% of Earth history we are currently living in, even though we are so fond of attempts at deciphering and putting it into a coherent perspective. Who dares to define what it is like to live in "the now" in times when collective narratives are breaking apart rapidly and data is picked and interpreted at will?

In short, uncertainty is not a very meaningful category when examining simulations, no matter if they deal with the past, the future or the present. Simulation, instead, is a way of expressing an experimental and time-transgressive "real"—that is, again, "everything that is possible"—and this powerful generativity is manifest in a quite splendid and colourful way in the practice of paleoclimate modelling.

Yes, deep-time paleomodelling tests geoscientific knowledge to its conceptual limits. Nevertheless, it still presents a fruitful effort to gain insight into a worldly reality too overwhelming to neglect. Testing and experimenting is the realm of computer simulation, which is not something hermetic but operates in an open and self-conscious way. Through traversing times and similitudes, paleosimulations show a very skilful way of dealing with uncertainty and provide a very legitimate insight to the deep pasts, deep futures, and deep presents that climate change poses to us.

---

[1] The first one being Christoph Rosol, Hauling Data. Anthropocene Analogues, Paleoceanography and Missing Paradigm Shifts, *Historical Social Research* 40.2 (2015) (Special Issue: *Climate and Beyond. The Production of Knowledge about the Earth as a Signpost of Social Change* ed. by Andrea Westermann, Christian Rohr), 37–66.

[2] Patrick J. Bartlein, Steven W. Hostetler, Modeling paleoclimates, *Developments in Quaternary Science* 1 (2003), 565–584, here p. 565.

[3] Alan M. Haywood, Andy Ridgwell, Daniel J. Lunt, Daniel J. Hill, Matthew J. Pound, Harry J. Dowsett, Aisling M. Dolan, Jane E. Francis, Mark Williams, Are there pre-Quaternary geological analogues for a future greenhouse warming?, *Philosophical Transactions of the Royal Society A* 369 (2011), 933–956, here p. 933.

[4] Rosol, *Hauling Data* (see note 1).

[5] W. Lawrence Gates, Paleoclimatic Modeling – A Review with Reference to Problems and Prospects for the Pre-Pleistocene, in: NRC Geophysics Study Committee (ed.), *Climate in Earth History*, Washington, D.C.: National Academic Press 1982, 26-42, here p. 35.

[6] See e.g. Pascale Braconnot, Sandy P. Harrison, Masa Kageyama, Patrick J. Bartlein, Valerie Masson-Delmotte, Ayako Abe-Ouchi, Bette Otto-Bliesner, Yan Zhao, Evaluation of climate models using paleoclimatic data, *Nature Climate Change* 2 (2012), 417–424, here p. 417. The term „sensor"—a device measuring or monitoring a physical property—has actually been used for quite some time for paleoproxies, see e.g. John E. Kutzbach, Diagnostic Studies of Past Climates, in: *The Physical Basis of Climate and Climate Modeling: Report of the International Study Conference in Stockholm, 29 July - 10 August 1974.* Geneva: World Meteorological Organization 1975, 119–126, here p. 119. Alan D. Hecht, Roger Barry, John Imbrie, John Kutzbach, J. Murray Mitchell, Samuel M. Savin, Paleoclimatic research: Status and opportunities, *Quaternary Research* 12.1 (1979), 6–17 use „sensing" and „sensors" only in quotation marks. The history of the idiom „environmental sensing" would certainly deserve a study of its own. While Jennifer Gabrys investigates the recent „explosion of environmental sensing technologies" in her book „by focusing on the becoming environmental of computation" and the „becoming computational of environments", the metaphorical usage of the term in the sense of environments or organisms that deliberately act as sensor technologies is entirely absent from her discussion, Jennifer Gabrys, *Program Earth: Environmental Sensing Technology and the Making of a Computational Planet,* Minneapolis: University of Minnesota Press 2016, p. 4ff. All while it is obvious that sensing itself is a property borrowed from the life sciences, its attribution to either life or technology is already blurred at the beginning of the environmental sciences. Uexküll starts his „Foray" with the description of the blind and deaf tick sensing its prey and the question whether „the tick is a machine", Jakob von Uexküll, *A Foray into the Worlds of Animals and Humans. With A Theory of Meaning*. Minneapolis: University of Minnesota Press 2010 (orig. 1934), p. 45. It seems plausible to suspect that with the advent of cybernetics and its stressing of the correspondence between input devices for computing machinery and the sensory apparatus of the nervous system, the distinction became basically invalid and replaced by the universal notion of information. According to the OED, the first mentioning of the term „sensor" then appears in 1958 in the context of missile guidance: an accelerometer „measuring the magnitude and feeding the resultant quantity into a computer", Anonym., The spinning fluid speedometer, *The New Scientist* 3.73 (1958), 22.

[7] „Klimazeugen" is the traditional term in German.

[8] Lisa Gitelman (ed.), *"Raw Data" Is An Oxymoron*, Cambridge, MA: MIT Press 2013.

[9] Willem Schinkel, Making climates comparable: Comparison in paleoclimatology, *Social Studies of Science* 46:3 (2016), 374–395.

[10] Schinkel, Making climates comparable (see note 9), p. 391

[11] Such a service for the international community provides, for instance, the data publisher PANGAEA at the Center for Marine Environmental Sciences in Bremen (MARUM).

[12] Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*, Cambridge, MA: MIT Press 2010, p. 323ff.

[13] Braconnot et al., Evaluation of climate models (see note 6), p. 418.

[14] Michael N. Evans, Susan E. Tolwinski-Ward, Diane M. Thompson, Kevin J. Anchukaitis, Applications of proxy system modeling in high resolution paleoclimatology, *Quaternary Science Reviews* 76 (2013), 16-28

[15] Adapted from Evans et al., Applications of proxy system modeling (see note 14), Fig. 1, p. 17.The original caption states: "Conceptual generalized proxy system model. An archive is the medium in which the response of a sensor to environmental forcing may be observed. A proxy system model is an idealized representation of the complete proxy system or selected components thereof."

[16] The notions Mode 1 and Mode 2 science were introduced by Michael Gibbons, Helga Nowotny, Camille Limoges, Simon Schwartzman, Peter Scott, Martin Trow: *The New Production of Knowledge. The*

Dynamics of Science and Research in Contemporary Societies, London: Sage 1994. A valuable critique of this conceptual divide is stated in Gregor Schiemann: An Epoch-Making Change in the Development of Science? A Critique of the “Epochal-Break-Thesis”, in: Martin Carrier and Alfred Nordmann (eds.), *Science in the Context of Application*, Dordrecht: Springer, 431-453.

[17] Mark Williams, Alan M. Haywood, F. John Gregory, Daniela N. Schmidt, Deep-time perspectives on climate change: An introduction, in: Mark Williams, Alan M. Haywood, F. John Gregory, Daniela N. Schmidt (eds.), *Deep-time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies,* London: Geological Society of London 2007, 1–4, here p. 2.

[18] Masa Kageyama, Pascale Braconnot, Sandy P. Harrison, Alan M. Haywood, Johann Jungclaus, Bette L. Otto-Bliesner, Jean-Yves Peterschmitt, Ayako Abe-Ouchi, Samuel Albani, Patrick J. Bartlein, Chris Brierley, Michel Crucifix, Aisling Dolan, Laura Fernandez-Donado, Hubertus Fischer, Peter O. Hopcroft, Ruza F. Ivanovic, Fabrice Lambert, Dan J. Lunt, Natalie M. Mahowald, W. Richard Peltier, Steven J. Phipps, Didier M. Roche, Gavin A. Schmidt, Lev Tarasov, Paul J. Valdes, Qiong Zhang, Tianjun Zhou, PMIP4-CMIP6: The contribution of the Paleoclimate Modelling Intercomparison Project to CMIP6, discussion paper under review for *Geoscientific Model Development*, URL: http://www.geosci-model-dev-discuss.net/gmd-2016-106/ (last accessed March 24, 2017). For an example of the technical logistics of such comparisons see e.g. Paul J. Markwick, The palaeogeographic and palaeoclimatic significance of climate proxies for data-model comparisons, in: Williams et al. (eds.), *Deep-time Perspectives* (see note 17), p. 251–312, here p. 294ff.

[19] Robert J. Oglesby, Kirk J. Maasch, Paleoclimate modeling, Quaternary, in: Vivien Gornitz (ed.), *Encyclopedia of Paleoclimatology and Ancient Environments*, Dordrecht: Springer 2009, 709–716 and Christopher J. Poulsen, Paleoclimate modeling, pre-Quaternary, in: Gornitz, *Encyclopedia*, 700–709.

[20] John von Neumann, *Dynamics of the General Circulation*. Draft, Jul 29. 1955, reprinted in Joseph Smagorinsky, The beginnings of numerical weather prediction and general circulation modeling: Early recollections, in: Barry Saltzman (ed.), *Theory of Climate*, New York: Academic Press 1983, 3–37. See also Edwards, *A Vast Machine* (see note 12), p. 141.

[21] Richard L. Pfeffer, On the Design of a Numerical Experiment for the Study of the General Circulation of the Atmosphere, in Richard L. Pfeffer (ed.), *Dynamics of Climate. The Proceedings of a Conference on the Application of Numerical Integration Techniques to the Problem of the General Circulation held October 26-28, 1955, Institute for Advanced Study, Princeton, N.J.,* Oxford, New York: Pergamon Press 1960, 26–31, here p. 31.

[22] Norman A. Phillips, The general circulation of the atmosphere: A numerical experiment, *Quarterly Journal of the Royal Meteorological Society* 82 (1956), p. 123–164; see also John M. Lewis, Clarifying the dynamics of the General Circulation: Phillips’s 1956 Experiment, in: David A. Randall (ed.), *General Circulation Model Development: Past, Present, and Future*. London: Academic Press 2000, 91–125.

[23] Robert M. White, *Invitation sent to Philip D. Thompson for participation in a general circulation study group (incl. concept and revised program),* Sep 2, 1955. NCAR Archives, Philip Duncan Thompson Papers, 39, 1955, p. 2.

[24] Discussion, in: Pfeffer, *Dynamics of Climate* (see note 21), 115–136, here p. 132.

[25] John von Neumann, Some Remarks on the Problem of Forecasting Climatic Fluctuations, in: Pfeffer, *Dynamics of Climate* (see note 21), 9–11, here p. 10f.

[26] John von Neumann, *Letter to Harry Wexler*, May 19, 1955, Tel Aviv (thus signed „Jehuda”), Library of Congress, Manuscript Division, Harry Wexler Papers, 7, 1955,2. Apparently, von Neumann knew his C.E.P. Brooks: *Climate Through the Ages: A Study of the Climatic Factors and their Variations*. New York: Dover 1926 and was familiar with the mapping effort of Hurd C. Willett, The general circulation at the last (Wurm) glacial maximum, *Geografiska Annaler* 32 (1950), 179–187. Von Neumann gave his comments on a draft of Harry Wexler, Variations in insolation, general circulation and climate, *Tellus* 8 (1956), 480–494. He ended his letter with: “p.p. I still did not have time to write up my ideas on problems of climatic change,” time he was never able to get, before his death less than two years after this letter.

[27] von Neumann, Forecasting Climatic Fluctuations (see note 25), p. 9.

[28] Hubert H. Lamb, Paleoclimatology, *Meteorological Magazine* 1 (1963), 246–249, here p. 249. The talk that supposedly made that claim and thereby introduced Lamb to general circulation modeling was given by P. A. Sheppard, Basic ideas on the general circulation of the atmosphere, in: A. E. M. Nairn (ed.), *Problems in Palaeoclimatology. Proceedings of the N.A.T.O. conference, Newcastle-on-Tyne, January 1963*. London: Interscience Publishers 1964, 322–331.

[29] Janet Martin-Nielsen, A new climate. Hubert H. Lamb and boundary work at the UK Meteorological Office, in: Matthias Heymann, Gabriele Gramelsberger, Martin Mahony (eds.), *Cultures of Prediction in Atmospheric and Climate Science. Epistemic and Cultural Shifts in Computer-based Modelling and Simulation*. London: Routledge, forthcoming.

---

[30] J. Murray Mitchell, Theoretical paleoclimatology, in: Herbert E. Wright, David G. Frey (eds.), *The Quaternary of the United States*, Princeton: Princeton University Press 1965, 881–901, here p. 881.

[31] Mitchell, Theoretical paleoclimatology (see note 30), p. 899. Mitchell is referring to Joseph Smagorinsky, General Circulation Experiments with the Primitive Equations, *Monthly Weather Review* 91.3 (1963), 99–164, in which the first simulation of large eddies was carried out. Concurrently, Yale Mintz and Akio Arakawa were also undertaking some long-term integration experiments, seeing the study of "the climate of past geologic ages" as a potential application, Yale Mintz, Very long-term global integration of the primitive equations of atmospheric motion: an experiment in climate simulation, *Meteorological Monographs* 8.30 (1968), (Special Issue: *Causes of Climate Change*, ed. by J. Murray Mitchell*)*, 20–36, here p. 35.

[32] Hermann Flohn, Allgemeine atmosphärische Zirkulation und Paläoklimatologie, *Geologische Rundschau* 40.1 (1952), 153–178.

[33] Hermann Flohn, Grundfragen der Paläoklimatologie im Lichte der theoretischen Klimatologie, *Geologische Rundschau* 54 (1964), 504–515, here p. 505.

[34] Flohn, Grundfragen der Paläoklimatologie (see note 32), p. 509.

[35] E.g. Jill Williams, R. G. Barry, Warren M. Washington, Simulation of the atmospheric circulation using the NCAR Global Circulation Model with ice age boundary conditions, *Journal of Applied Meteorology* 13.3 (1974), 305–317; W. Lawrence Gates, The numerical simulation of ice-age climate with a global general circulation model, *Journal of the Atmospheric Sciences* 33 (1976), 1844–1873; Syukuro Manabe, Douglas G. Hahn, Simulation of the tropical climate of an ice age, *Journal of Geophysical Research* 82 (1977), 3389–3911. See for an overview Hecht et al., Paleoclimatic research (see note 6).

[36] *Interview of Syukuro Manabe* (Interviewer: Ronald Stouffer), 2007, Transcript, NCAR-Archives, p. 18. In a personal interview with the author in 2008 in Princeton, Manabe pressed a similar point by referring to the principle of Ockham's razor: "The secret of success is to make the system as simple as possible!"

[37] Syukuro Manabe, Richard T. Wetherald, The effects of doubling the CO_2 concentration on the climate of a general circulation model, *Journal of the Atmospheric Sciences* 32 (1975), p. 3–15.

[38] Kageyama et al., PMIP4-CMIP6 (see note 18).

[39] Barry Saltzman, Paleoclimatic Modeling, in: Alan D. Hecht (ed.) *Paleoclimate Analysis and Modeling*, New York: Wiley 1985, 341–396.

[40] In the 1920's the Serbian geophysicist and astronomer Milutin Milanković devised a correlation scheme in which the alternate growth and decline of ice sheets could be attributed to the different insolation patterns resulting from cyclical changes in a) the eccentricity of the Earth's movement around the sun, b) its rotational tilt and c) its axial precession. Milutin Milanković, Mathematische Klimalehre und astronomische Theorie der Klimaschwankungen, in: Wladimir Köppen and Geiger Rudolf (ed.), *Handbuch der Klimatologie*, Vol. 1, *Allgemeine Klimalehre*, Berlin: Borntraeger, 1930, pp. 1-176

[41] Edward N. Lorenz, The problem of deducing the climate from the governing equations, *Tellus* 16 (1964), p. 1–11; Edward N. Lorenz, Climatic determinism, *Meteorological Monographs* 8.30 (1968), 1–3.

[42] J. Murray Mitchell, Concluding remarks, *Meteorological Monographs* 8.30 (1968), 155–159, p. 158.

[43] Gates, Paleoclimatic Modeling (see note 5), p. 28.

[44] Hans Oeschger, J. Beer, Urs Siegenthaler, B. Stauffer, Willy Dansgaard, C.C. Langway, Late glacial climate history from ice cores, in James E. Hansen, Taro Takahashi (eds.), *Climate Processes and Climate Sensitivity*, New York: Wiley 1984, 299–306, see also Wallace P. Broecker, Dorothy M. Peteet, David Rind, Does the ocean-atmosphere system have more than one stable mode of operation?, *Nature* 315 (1985), 21–26.

[45] E.g. the Lorenz–Saltzman model is the simplest form of a description of non-linear processes in relation with the general circulation of the atmosphere, see. Thomas Stocker, *Introduction to Climate Modelling*, Berlin, Heidelberg: Springer 2011, pp. 128ff.

[46] Hermann Flohn, Can climate history repeat itself? Possible climatic warming and the case of palaeoclimatic warm phases, in: Wilfried Bach, Jürgen Pankrath, William Kellogg (eds.), *Man's Impact on Climate. Proceedings of the International Conference, Berlin, June 14-16, 1978*, Amsterdam: Elsevier Scientific Publishing 1979, 15–28, here p. 16.

[47] James C. Zachos, Gerald R. Dickens, Richard E. Zeebe, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics, *Nature* 451 (2008), 279–283, here p. 279; Ying Cui, Lee R. Kump, Andy J. Ridgwell, Adam J. Charles, Christopher K. Junium, Aaron F. Diefendorf, Katherine H. Freeman, Nathan M. Urban, Ian C. Harding, Slow release of fossil carbon during the Palaeocene–Eocene Thermal Maximum, *Nature Geoscience* 4 (2011), 481–485; Richard E. Zeebe, Andy Ridgwell, James C. Zachos, Anthropogenic carbon release rate unprecedented during the past 66 million years, *Nature Geoscience*. 9 (2016), 325–329.

[48] Charles Lyell, *Principles of Geology, being an attempt to explain the former changes of the Earth's surface, by reference to causes now in operation*, Vol. 3., London: A Spottiswoode 1833, p. 225, see also p. 55.

---

[49] Richard B. Alley, The Biggest Control Knob: Carbon Dioxide in Earth's Climate History, Bjerknes Lecture, AGU Fall Meeting, Dec 14-18, San Francisco, 2009, URL: https://youtu.be/RffPSrRpq_g (last accessed: March 24 2017), 27'30".

[50] Williams et al., Deep-time perspectives (see note 17), p. 2. Same expression here: Haywood et al., Are there pre-Quaternary geological analogues (see note 3), p. 934ff.

[51] Haywood et al., Are there pre-Quaternary geological analogues (see note 3), p. 949.

[52] Bruno Latour, Why Has Critique Run out of Steam? From Matters of Fact to Matters of Concern, *Critical Inquiry* 30.2 (2004), 225–248.

[53] Michel Serres with Bruno Latour, *Conversations on Science, Culture, and Time*, Ann Arbor: University of Michigan Press 1995, p. 66. See also Jane Bennett, William Connolly, The Crumpled Handkerchief, in: Bernd Herzogenrath (ed.), *Time and History in Deleuze and Serres*, London: Continuum 2012, 347–372, here p. 165f.

[54] Michel Serres, La simulation, technique nouvelle, ancienne tradition, *Clefs CEA (Commissariat `a l´´energie atomique)* 47 (2003), 2–5, here p. 5 (translation by author).

[55] Michel Serres, *Biogea*, Minneapolis: University of Minnesota Press 2012.

[56] Serres, *Conversations* (see note 53), p. 60

[57] "Michel Serres is naive and gullible beyond description. Every time a revolution or a 'coupure epistémologique' or an intellectual *pronunciamiento*, has definitely reversed the order of things, he still believes in what has been reversed; worse, he does not know how to choose between the past and the present, the losers and the winners." Bruno Latour, The Enlightenment without the Critique: A Word on Michel Serres' Philosophy, in: A. Phillips Griffiths (ed.), *Contemporary French Philosophy*, Cambridge: Cambridge University Press 1987, p. 83–97, here p. 83.

[58] Bartlein, Hostetler, Modeling paleoclimates (see note 2), p. 565.

[59] Bartlein, Hostetler, Modeling paleoclimates (see note 2), p. 565.

[60] Bartlein, Hostetler, Modeling paleoclimates (see note 2), p. 565.

[61] Peter Galison, Computer Simulations and the Trading Zone, in: Peter Galison, David Jay Stump (eds.), *The Disunity of Science. Boundaries, Contexts and Power*, Stanford: Stanford University Press 1996, 118–157, here p. 155 and p. 137 respectively.

[62] Etienne Benson, The Virtual Field, *Technosphere Magazine* (2016) URL: http://www.technosphere-magazine.hkw.de/p/f86f17b0-8a6c-11e6-8b42-2ff16d371dbf (last accessed March 24, 2017).

[63] Claus Pias, On the Epistemology of Computer Simulation, *Zeitschrift für Medien- und Kulturforschung* 1 (2011), 29–54.

[64] Helga Nowotny, *The Cunning of Uncertainty*. Cambridge: Polity Books 2015, p. xii.

[65] Nowotny, *The Cunning* (see note 64), pp. 167f.

[66] Pias, On the Epistemology (see note 63), p. 54.

[67] Amy Dahan-Dalmedico, Models and Simulations in Climate Change: Historical, Epistemological, Anthropological, and Political Aspects, in: Angela N. H. Creager, Elizabeth Lunbeck, M. Norton Wise (ed.), *Science Without Laws: Model Systems, Cases, Exemplary Narratives*, Duke University Press, 125-156, here p. 151.

[68] Timon Beyes, Claus Pias, Debatte: Transparenz und Geheimnis, *Zeitschrift für Kulturwissenschaften* 2 (2014), 111–117, here pp. 114f, in reference to Hans Ulrich Gumbrecht: *Unsere breite Gegenwart*, Berlin: Suhrkamp 2010.