Editorial Commentary

Climate models and modeling: an editorial essay

Modeling is a central concept, a central tool in climate research. Models are telling us how the future may develop in the next 100 years, the public is told by some experts, while others insist that all such perspectives rest on shaky mathematical constructs with little connection to reality. This confusion has much to do with different epistemological cultures in different quarters of science and among the public at large. The word "model" simply means quite different concepts. These range from process-based dynamical models—which serve as a kind of substitute reality in meteorology, oceanography, and climate science—to pre-forms of theory in physics or to mechanical analogs in engineering or in public education.[1] To overcome this confusion requires an appropriate explanation what this term "modeling" usually implies in the field of climate science. The relevant questions are:

1. How are climate models constructed?
2. How are the various dynamical processes, which are significant for the climate system, described in such models?
3. How are climate models used to obtain new knowledge?

In the following, I briefly browse through a number of issues relevant for the understanding of models and their usage in the field of climate research. These will be the issues that will be covered in this section "Climate Models and Modeling" of the *WIREs Climate Change* review journal. Before doing so, a brief account of the history of ideas in the field of climate research may be useful.

THE ROAD TOWARD CLIMATE MODELING

The term "climate" has undergone a number of meanings, in different disciplines and times (cf. Ref. 2). An important climate researcher was Alexander von Humboldt, who wrote in his work *Cosmos, A Sketch of a Physical Description of the Universe*, initially published in 1845:

> "The term climate, taken in its most general sense, indicates all the changes in the atmosphere, which sensibly affect our organs, as temperature, humidity, variations in the barometrical pressure, the calm state of the air or the action of opposite winds, the amount of electric tension, the purity of the atmosphere or its admixture with more or less noxious gaseous exhalations, and, finally, the degree of ordinary transparency and clearness of the sky, which is not only important with respect to the increased radiation from the earth, the organic development of plants, and the ripening of fruits, but also with reference to its influence on the feelings and mental condition of men."

Thinking about climate meant always to think also about the impact on people and their culture.

A first significant change took place in the late 19th century, or so, when leading persons such as the Austrian Julius von Hann (1839–1921) characterized climate as "the totality of meteorological phenomena, which characterize the (average) condition of the atmosphere in any position of the earth's surface." In this view, climate was again the atmosphere—but the challenge was the description, the careful analysis, of the state of the "(average) condition." Thus, the global climate was mostly the sum of all regional climates. "Climate" and "weather" were differentiated: Weather was the transient, real, local atmospheric condition of the day; climate was the statistics of weather calculated over long periods of time, and usually for larger geographic areas. Or, in modern words, weather is a random phenomenon, the properties of which are described by its climate. These statistics are determined from a series of measurements and observations of atmospheric values, primarily temperature, precipitation, and wind speed. The main emphasis of climate research lay in a geographical description comparing different regions, and in the classification of the averages of variable weather conditions over longer periods of time. Climate appeared more or less static.

Only when scientists were no longer limited to observations at the surface, due to technical innovations in the 1920s, did the third phase of climate research begin. Climatology became a special branch of science, dealing mostly with the physical description of climatological processes. More and more physicists turned to the investigation of atmospheric and oceanic occurrences (e.g., Ref 3). The hitherto traditional link to geography loosened in favor of a new discipline, "Physics of the Atmosphere and/or the Ocean." The

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idea of the global climate being merely the sum of regional climates gave way to a different concept, which in modern terms may be characterized by the concept of "downscaling"—the global climate is the response of the global system to global forcing, the regional climate is the result of the interaction of the global climate with regional physiographic details (e.g., Ref. 4). Without this concept of an integrated, interacting physical system, climate modeling would be impossible. The idea of constructing climate models is based on the idea that the effect of truncating smaller scales can be dealt with by a summary description of the effect of such processes—a process called "parameterization." At the same time, the insight was accepted that climate would not be constant, the variations of which could be "averaged away" by considering statistics derived from 30 year, or so, time windows.

Nowadays, the climate system is understood as the physical-biogeochemical system which generates the time-variable statistics of the state of the participating components. It includes of course the atmosphere, but the atmosphere is merely a part, albeit a very essential one. Another very important part is the global ocean, mainly because of its much larger inertia than that of the atmosphere. Other components are the cryosphere, with sea ice and ice sheets; the biogeochemical cycles, which influence the radiation balance; the vegetation, with its ability to modify the surface of the Earth and its influence in biogeochemical cycles. And finally also humans, who by their action not only influence the biogeochemical cycles but also modify land surfaces. Whether the sun, other cosmic processes and volcanic activity are part of the climate system or are considered external is a matter of definition—but they certainly exert a significant influence on the climate system. Only in this last phase of conceptual thinking have dynamical models, which are based on the representation of a variety of processes, become available[5]—and they have transformed climate research into a science with results of immediate relevance not only for our world view but also for deliberations about Earth management.

This section of *WIREs Climate Change*, therefore, will feature a series of articles reviewing our knowledge about how to model the global Earth system, regional climate subsystems, the coupling of atmosphere and ocean, biogeochemical cycles, vegetation and land use, and ice sheet and sea ice dynamics. The potential of combining climate models with economic models will also be addressed.

MODELS AND PARAMETERIZATIONS

In climate science, two types of models are in use.[1] One sort are *conceptual models*, which describe in a maximum simplification the basics of the climate system or a subsystem thereof. In a sense, they constitute "theory," as they describe the effect of first-order physical processes. They usually take the form of mathematical equations, which allow for analytical manipulation. The other type is that of *quasi-realistic models*, which seek to maximize complexity—maximize given the computational resources. Of course, this model complexity may optimize different aspects, for instance, spatial resolution [the global climate model (GCM)-type] or the number of components (the so-called intermediate complexity models). These models take the form of lengthy and complex programming code to be executed on an advanced computer. Such models represent a tool for "numerical experimentation" and various applications, in particular the design of possible futures. In the following, we deal only with these quasi-realistic models.

In the "real system", for which we can define an "inside" and an "outside," there are infinitely many processes to consider, and infinitely many influences that act upon that system, as sketched in Figure 1a.

A model of the "real" system is depicted in Figure 1b. In the model only a limited, finite number of processes is described. The number of external influences is strongly reduced, and the effect of some of the non-considered processes (such as clouds in GCMs) is taken into account not by describing the dynamics of clouds, but by specifying the expected physical effect of clouds. In the example of Figure 1, only the processes P_1–P_3 are considered to be modeled, whereas P_4 is in this way "parameterized." Models are *smaller, simpler,* and *closed* in contrast to reality, which is always *open*.

"Smaller" means that only a limited number of the infinite number of real processes can be accounted for. In the case of an atmospheric model or an oceanic model, the unavoidable discretization means that from the almost unlimited range of scales in reality, only a limited interval can be accounted for by the model. A global model describes planetary waves and cyclones, for example, but no boundary layer turbulence in any detail. Similarly, an ocean model resolving internal gravity waves will hardly describe the dynamics of thermohaline circulation of the world's oceans.

"Simpler" means that the description of the considered processes is simplified. Furthermore, some of the links to the processes, which are not described by the model, are indirectly accounted for by means of "parameterizations" (see above). "Closed" means that models are integrated with a limited number of completely specified external forcing functions. As elaborated by Oreskes et al.,[7] this is an important philosophical limitation of environmental models, as

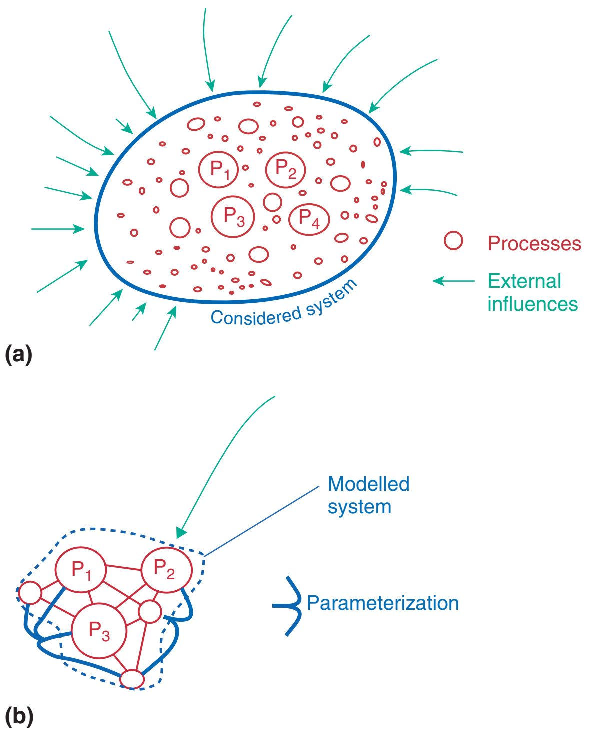

FIGURE 1 | Sketches of (a) a real system, in which an infinite number of processes P_i (open circles) is present, and upon which an infinite number of external forces (arrows) act; (b) a modeled system, in which only a limited number of processes (open circles) and their interactions are represented, and in which the number of external forces is also limited (arrow). Parameterizations are indicated by solid lines crossing the dashed-line border of the model.[6]

it implies that the "right" answer of a model may be due to either the "correctness" of the model or to a coincidental balance of an incorrect model response and the effect of an unaccounted external influence.

This insight leads to the conclusion that models cannot be "verified," in the sense that we can prove that a response of a model to a certain forcing is "right" because of the "right reasons." It also raises big questions about whether we can "falsify" a model. In a trivial sense, all models are wrong and some—not only cynics—even claim that all lengthy and complex programming codes contain an unknown, but non-zero, number of elementary coding errors. So, when do we assign the assessment "false" or "flawed" to a model?

Review articles will be commissioned by this section of *WIREs Climate Change* on parameterizations (the representation of key processes without resolving them), the mathematics of numerical representation of climate models, the utility of intermediate complexity models, and the skill and uncertainty of models. It will also be discussed what type of surprises due to progress in modeling may be possible.

DIFFERENT APPLICATIONS

In providing a virtual reality, quasi-realistic computer models can be employed for various purposes. In particular, "experiments" impossible with the real climate system can be carried out. In the framework of the physical sciences, such models allow the testing of hypotheses and extended simulations. Typical hypotheses concern the relevance of certain processes. Simulations generate complex data sets that allow detailed diagnostic studies of processes for which adequate observational evidence is lacking. In applied science, such models serve to interpret sparse and uncertain observational data, to forecast future states and to derive detailed scenarios of plausible future developments.

In a series of review articles, these applications will be elaborated upon in some detail. Here, I want to give a first brief sketch of the spectrum of these applications. Figure 2 sketches the different purposes of various climate models, generating either practical knowledge to be used in social contexts or in generating dynamical insight to further scientific knowledge. Climate models are used for all these purposes, and the various articles in the WIREs series will demonstrate these applications in some depth.

Hypothesis Testing

Experiments with computer models allow the formulation and testing of hypotheses. Such experiments are called "numerical experiments." The aim is to understand and comprehend the system. The typical question is: What are the most important processes governing a dynamical regime? Such experiments are therefore a tool to be used in fundamental scientific research. On the other hand, the impact of some human interference on the system may also be studied in a numerical experiment. Here, the effort is part of applied science. Some typical examples would be what is the effect of cirrus clouds (e.g., Ref. 8) or of different vegetation types on climate, what was the effect of the release of large volumes of melt water into the Atlantic Ocean at the end of the last glacial period, or how does the physical barrier of the American isthmus effect the global oceanic circulation (e.g., Ref. 9)?

Simulation of Present and Past States

The dynamics of actual and past climate regimes is of major interest for environmental sciences. What is the energy cycle of the atmosphere? How much eddy potential energy is transformed into eddy kinetic energy in cyclones? Often, the observations are often not sufficient for such an analysis. But the output

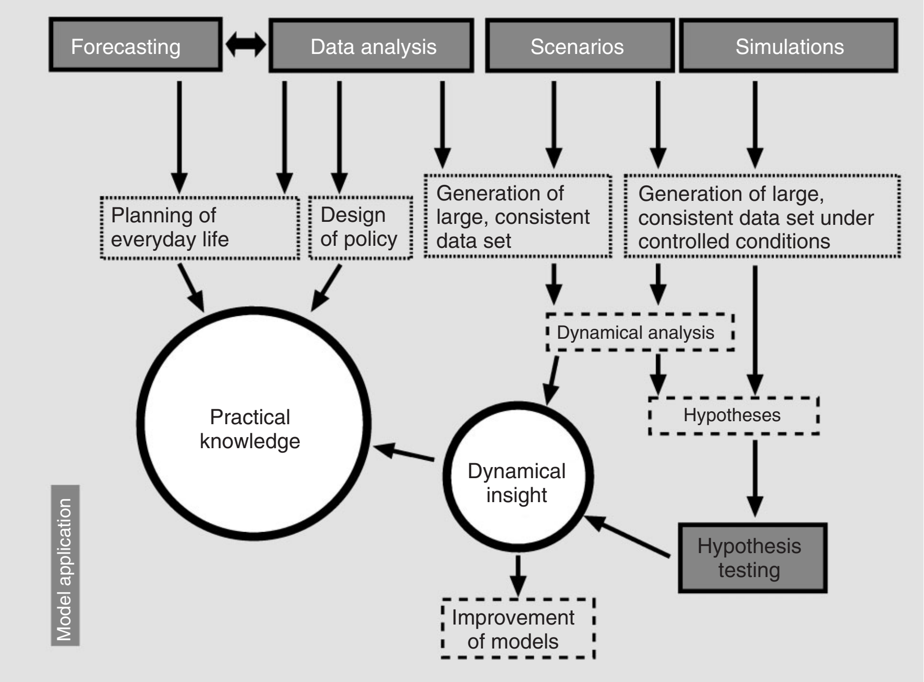

FIGURE 2 | Sketch of the purposes of different climate models, in generating either practical knowledge to be used in social contexts or dynamical insight to further scientific knowledge.[1]

of an atmospheric model simulation often provides a basis for doing so. The reconstruction of paleoclimatic states is also a topical task in contemporary climate science (e.g., Ref 10). Although some features of past climates may be deduced from various proxy data, such as isotope ratios in ice cores and width of tree rings, a spatially complete and dynamically consistent reconstruction can be made only with a climate model subjected to the appropriate forcing conditions of past eras, such as different land-sea distribution, atmospheric composition, and orbital parameters.

Data Analysis

A relatively new application of quasi-realistic models is the "dynamically consistent interpolation" of irregularly distributed inaccurate observational data (e.g., Ref 11). Here, the task is to estimate the unknown state—for instance, a detailed weather map—from the limited number of observations and the dynamically consistent forecast of a quasi-realistic model. Complete 3- or 4-dimensional representations of the atmospheric (e.g., Ref 12) and of the oceanic synoptic state (e.g., Ref 13) are constructed in "re-analyses." They allow the study of processes which are not directly observable, such as the global meridional transports of heat and water.

Forecasts or Predictions

An important application of specifying any probable or possible climate future is forecasting the El Nino-Southern Oscillation (ENSO) phenomenon. Experiments with climate models are also presently underway to examine the potential for decadal climate forecasting.[14]

Simulation of Plausible and Dynamically Consistent Future States

Predictions of the detailed future development of the atmosphere are limited to lead times of mostly a few days, at least in mid-latitudes. Society and stakeholders thus request a different type of prediction, namely the prediction of plausible future statistics of the atmosphere decades or centuries into the future, conditional upon certain human activities. These conditioning human activities (e.g., future changes in land use or industrial emissions of greenhouse gas) are almost never themselves predictable, so neither can the statistics of the atmosphere be fully predictable. Instead, one refers to scenarios. When the assumptions about the human activity are plausible, then the resulting climate scenario can be plausible—given that the model is capable of simulating the altered climatic state. When the assumptions are likely, the scenario can be likely. When the assumptions describe an unlikely human development (e.g., stopping all fossil fuel use next year) then the climate scenario becomes unlikely. Scenarios of future anthropogenic climate change are for the public the most intriguing applications of quasi-realistic climate models.

Review articles dealing with the issue of climate predictions versus climate scenarios and about prospects for decadal climate predictions will accompany articles on specific issues such as the utility of modeling in detection and attribution studies and in the trends and predictions of tropical cyclones.

ADDED VALUE

As already suggested earlier, models (like theories and other cognitive constructs) cannot be verified.[1,7,15] Even if models correctly describe reality under one set of circumstances, one cannot be sure that they will also do so under a different set of circumstances. The logician concludes from this fact that models can only be falsified but not verified. They are false if they do not "predict" reality correctly. This categorical statement is, however, not appropriate for models of environmental systems where the notion of correct or incorrect prediction is not well-defined. The appropriate question to ask is "how well does a model reproduce reality?" The question is not whether a model is right or wrong, but how good it is. Quantitative measures need to be developed for answering this question. And the purpose of the model needs to be included when trying to provide an answer.

Therefore, the weaker concept of model *validation* is introduced. One only requires that the model results are consistent with observations. One does not claim that the model is "correct," but only that it "works."

A useful concept is that of *analogs*. Following the philosopher of science Mary Hesse,[16] models have positive, neutral and negative analogs with reality. *Positive* analogs are common properties, and a validation strategy should show that they prevail both in reality and in the model. *Neutral* analogs are properties for which it is not known whether they are common properties, and *negative* analogs are properties that are not shared by model and reality. In the case of climate models, positive analogs are the conservation of mass, energy and momentum, neutral analogs are the sensitivity of the model's climate to changing greenhouse gas concentrations, and negative analogs are the propagation of sound waves in the ocean or atmosphere and the existence of a time step in the numerical code. The task of validation is to determine the positive and negative analogs and to assess whether the extent of the positive analogs makes the model suitable for certain applications.

The added value of climate modeling comes from assuming that the neutral analogs are actually positive ones: that a response of a climate model to a forcing is actually the response that the environmental system would show if subjected to the forcing without any other changes. A forecast prepared with such a model is hoped to coincide with the actual development to be observed in the future.

Even if a model is validated—i.e., the existence of a series of relevant positive analogs confirmed–there is no certainty that these analogs remain positive when the model operates with parameters outside the range covered by the empirical evidence used for validating the model. If a climate model describes the present climate well, this is no proof that it describes paleoclimatic states or future states of a warmer climate well. There may be numerous good reasons to *believe* in a model's skill in doing so, but there remains always the possibility, albeit sometimes a small one, that relevant aspects of the non-observed part of the parameter space are not sufficiently taken into account.

The "Climate Models and Modeling" section of *WIREs Climate Change* will address the "added value" of models specifically with respect to regional models. Review articles are also foreseen about how to evaluate models, how to construct knowledge with models in general, about the evaluation of climate models and, specifically, the falsification of climate models used in experimentation and scenario construction. Links and some joint reviews are made with other WIREs Domains dealing with "Palaeoclimates and Current Trends," "Integrated Assessment of Climate Change," and "The Social Status of Climate Change Knowledge."

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