Max-Planck-Institut
für Meteorologie

Conceptual modeling at MPI-M

The Max Planck Institute for Meteorology (MPI-M) develops complex Earth system and climate models. To investigate and understand processes, the scientists also work with conceptual models in a variety of ways.

The MPI-M is worldwide known for the development of global coupled climate and Earth system models. These models are very complex and include all important components of the climate system: atmosphere, ocean, land and ice as well as biogeochemical cycles, such as the carbon cycle. It is remarkable that all model components are developed at MPI-M.

However, many MPI-M scientists also develop and use conceptual models to answer research questions. Their purpose is the development and verification of theories or to serve as pedagogical tools to understand processes and phenomena. Conceptual models are strongly simplified models. They help us to investigate correlations and processes in nature and in complex Earth system models. In a conceptual model, an attempt is made to simplify a physical system and reduce it to its fundamental processes in a way that it describes the essence of the system.

An example: Katherine Fodor, a PhD candidate in the Max Planck Research Group “Turbulent Mixing Processes in the Earth System”, studies the daytime atmospheric boundary layer. The boundary layer can be influenced by many factors, but in order to investigate the key processes of convection and entrainment, she uses a conceptual model. In her conceptual model, the boundary layer is represented as a turbulent flow over a smooth surface, heated from below and growing into a stably stratified environment. In contrast to complex Earth system models, where turbulence is parameterized, in her simplified model, turbulence can be resolved explicitly. A parameterization of turbulence is an inadequate representation of the real physics of turbulent flows in the boundary layer. In Katherine Fodor´s conceptual model, the governing flow equations are solved numerically and all scales of turbulent motion are resolved, eliminating the uncertainties associated with parameterizations. Thus, Katherine Fodor can study small-scale processes near the Earth's surface and in the entrainment zone, which are important for the development of the boundary layer. These insights would be impossible to gain from a complex Earth system model.

This example illustrates one application of conceptual models. A simplification of this kind is an aid to come to a process understanding. It is a good strategy for approaching research questions. Conceptual models are always specifically tailored to a particular problem. Further examples from the three departments of MPI-M, “The Atmosphere in the Earth System”, “The Ocean in the Earth System” and “The Land in the Earth System”, show how conceptual models can be applied to a variety of research questions.

Ann Kristin Naumann, for example, is a group leader in the department “The Atmosphere in the Earth System” and has developed a simplified model that helps her to understand how differences in radiative cooling in the lower layers of the atmosphere can drive shallow circulations. Shallow circulations are thought to be important for the organization of shallow and deep convection in the tropics. The conceptual model represents key characteristics of the lower atmosphere (1-2 km) and the trade wind shallow cumulus regime such as the cloud base height and average precipitation amount.

Ann Kristin Naumann shows with her model that shallow circulations can be driven by gradients in radiative cooling as well as by surface temperature gradient. The latter has been the dominant paradigm for explaining how patterns of sea-surface temperatures influence the position and strength of deep convection. This also suggests that radiative effects of water vapor in the lower troposphere may play a very active role in the coupled dynamics of the tropics.

Ann Kristin Naumann, too, isolates key processes of the system to be investigated which is not possible in this way in complex Earth system models. Once a suitable conceptual model has been formulated, this reduced set of equations can be used to analyze the system's response to various conditions. In this particular case, Ann Kristin Naumann was able to explain why vast areas of cloud-free conditions over the tropical oceans are very unlikely in the absence of mesoscale convective organization. She also showed how a radiatively driven shallow circulation is able to suppress convection in colder areas and enhance it in warmer areas.

Sally Dacie, a PhD candidate in the department “The Atmosphere in the Earth System”, uses a conceptual model to investigate the tropical tropopause, the boundary layer between the troposphere below and the stratosphere above. The tropical tropopause is colder than the troposphere below it and the stratosphere above it, which makes it particularly sensitive to changes in the atmospheric composition. Additionally, it is affected by dynamics occurring in both regimes, convection in the troposphere and large-scale upwelling in the tropical stratosphere. Since complex Earth system models cannot consistently predict the development of this layer, Sally Dacie´s approach was to develop a conceptual model in order to understand the role of several different factors. She develops it together with Lukas Kluft, a PhD candidate at Universität Hamburg and the International Max Planck Research School. The model is a one-dimensional radiative-convective equilibrium model and represents the tropical atmosphere in a single column from the surface upwards. The two main processes in this model are the radiative transfer and a simple convective adjustment, which takes energy from the surface and uses it to warm the troposphere. Using this model, she examines various simple assumptions about convection and how different gases (ozone, CO_2 and water vapor) influence the tropical tropopause.

Martin Claussen, director and head of the department “The Land in the Earth System”, was years ago interested in the question why the Sahara was green 6000 years ago and not a desert like today. To answer this question, he used models of medium complexity, more complex climate models and a conceptual model to investigate the interaction of atmosphere and vegetation in subtropical deserts. First, he compared individual parameters in order to investigate certain processes, for example, the vegetation spread in dependency with precipitation or vice versa precipitation in dependency with the vegetation spread. The model developed by *Brovkin, Claussen et al.* represents multiple stable states in the system: a “desert” equilibrium with low precipitation and absent vegetation and a “green” equilibrium with moderate precipitation and permanent vegetation cover (*Brovkin et al., 1998*). The conceptual model was applied to interpret the results of two climate-vegetation models: a comprehensive coupled atmosphere-biome model and a simple box model. In both applications, two stable states exist for the Western Sahara for the present-day climate, and only a green equilibrium is found for the mid-Holocene climate. The latter agrees well with paleo-reconstructions of Saharan climate and vegetation. Furthermore, it is shown that for present-day climate the desert equilibrium is more probable, explaining the existence of the Sahara desert as it is today. The authors were able to use the conceptual model to predict that the Sahara had to spread rapidly a few thousand years ago. This, in turn, was confirmed by simulations with the Earth system model of MPI-M (MPI-ESM). In fact, some paleoclimatic findings that were discovered later point to a rapid end of the so-called "green Sahara" a few thousand years ago (*Claussen et al., 2017*).

In the department "The Ocean in the Earth System" conceptual models are applied for the understanding of the Atlantic Meridional Overturning Circulation (AMOC). The general intention to use conceptual models in oceanography does not differ from the use in atmospheric science. Tim Rohrschneider, for example, is currently investigating the global overturning circulation across both hemispheres and is trying to estimate the strength of the northward transport. He focuses on the upper branch of the AMOC. After the more diagnostic evaluation of output from complex models, he uses conceptual models to investigate the correlation between the strength of the meridional flow and different parameters, such as the depth of the maximum overturning. Tim Rohrschneider uses individual equations which relate a set of parameters or variables, for example, the thickness of the pycnocline (boundary separating two liquid layers of different densities) and the meridional density gradients. In this way, the complexity is highly reduced and the changes in the AMOC can be derived and understood from the interplay of the parameters or variables. Simple box models are particularly suitable as conceptual models. They are very popular for gaining a general understanding of, for example, the horizontal convection between two regions. *Stommel´s* box model is famous—it can be used to explain the thermohaline circulation underlying the AMOC.

Jochem Marotzke, director at MPI-M and head of the department "The Ocean in the Earth System", already 30 years ago (among others in his dissertation) worked with the box model of *Stommel*. He developed and simplified it in his own work, thereby playing a decisive role in shaping the understanding of the AMOC (*e.g. Marotzke, 2000*). In addition to the strategy of using conceptual models to explain and understand research questions and contexts, he also appreciates the conceptual models as pedagogical tools in teaching. His lectures on climate dynamics, for example, are based less on fluid dynamics than on insights gained from simple conceptual models.

Conclusion

Conceptual models help us to understand processes and correlations. They are simplifications of more complex processes and include the essential parameters and equations that are necessary to gain knowledge. The simplification of the physical system to the decisive parameters or processes requires great intellectual performance. For the simplification of the process studies, correlations must be well understood in advance so that one can ask the decisive questions that are to be solved with a conceptual model. Epistemologically, conceptual models are more demanding and challenging than complex models. It is difficult to verify the quality of a conceptual model because it is so far from the complex reality. In the case of publications, this occasionally leads to an unfavorable assessment of the reviewers who may find that the simplification is inadmissible. Nevertheless, conceptual models are an excellent strategy for getting to the bottom of research issues.

Publications

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