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`Hello world!` Teaching an interdisciplinary understanding of climate modelling

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Abstract. Climate models are not just physics translated into computer code. They are powerful actors influencing and influenced by humans. Thus modelers need to learn and modeling courses need to teach not only the techniques of numerical discretisation and the physical understanding of the climate system, but also the underlying motivations, the uncertainties and the societal embededness of the modeling approach. Following a design-based research approach, this study develops a course at Bachelor level that aims to teach students such interdisciplinary perspectives. With a reflective open-ended exercise, we elicit students' learning process through challenging climate modeling topics. We find that the students learn to appreciate the complexity of climate models and the intricacies of scientific practice itself, highlighting for example the role of values in science. The exercise reveals few misconceptions and no major hurdles in the students' learning that may have been expected from the interdisciplinary nature of the material. We thus conclude that the course is a practice-proven approach to teaching the physical basis of climate modeling as well as its critical reflection. Together with the openly shared material, it supplies an inspiration and practical template for lecturers to include more interdisciplinary content and reflection into their modeling courses.

1 Introduction

Geoscientists are trained to think of climate change as a technical issue. In its simplest form, it is a problem of greenhouse gas emissions. Diving deeper, it relates to an entanglement of Earth system processes and compartments, providing ample justification for detailed investigations of those. To cope with this immense complexity and to tame it in order to provide projections, general circulation models (GCMs) have been developed. GCMs solve the equations of fluid dynamics numerically and include other (parameterised) computations of for example radiation and clouds' formation or effects (Gettelman and Rood, 2016; Easterbrook, 2023). They have gained authority in climate science and beyond (Sundberg, 2007; Heymann, 2020). GCMs

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have allowed investigating the threat of climate change in the first place, raised it on the political agenda, and are exceptional tools for attribution, process and sensitivity studies (Shackley et al., 1998; Edwards, 2001; Parker, 2003; Heymann, 2013),

Thus modelers yield powerful tools, yet these are not neutral. On the one hand, they are not built straight from physical principles. Instead, modeling involves "literally thousands" of "unforced" methodological choices (where one option is not "objectively better" than the alternatives) (Ward (2021) quoting Winsberg (2012)). These allow human influences to enter. In environmental modeling, development decisions have been shown to be influenced by modelers' habits (Babel, 2019), context (Addor and Melsen, 2019; Melsen, 2022), and values (Undorf et al., 2022). On the other hand, GMCs shape climate science as well as society and the public understanding of climate change. They tighten the grip of natural sciences around the understanding and discussion of climate change, emphasizing projections and a problem-solution or managerial policy framing (Shackley et al., 1998; Hulme, 2008; Mahony and Hulme, 2016). For example, Heymann et al. (2017b) criticise that GCMs sidelined alternative approaches to understanding climate. The global view propagated by GCMs restricts the space of imaginable interventions (Heymann et al., 2017b). It is also separated from local, personal experience and perception (Mahony and Hulme, 2018).

While the issues sketched above have become part of the scientific debate and motivated the reflection on good modeling practices, they have yet to reach many modelers and model developers themselves. For informed and active reflection to become part of modeling practice, it also needs to be integrated into modeling education. In addition to learning the physical and technical basis of how to construct numerical models, modelers also need to learn to reflect on other influences and model limitations, such as modeling motivations, model uncertainties, and models' historical development.

A particular motivation and challenge for this kind of learning lies in the inherent interdisciplinarity. Students should learn the actual modeling application (model building and use), as well as the historical and philosophical reflection on it. Alves (2012) highlights that especially for Earth System research, this interdisciplinarity is key, as the field needs to grapple with attribution of environmental changes as well as societal responses. Similarly, Rafolt et al. (2019) argue that socio-scientific issues like climate change require both scientific literacy and critical thinking. For hydrological modeling, Remmers et al. (2025) argue that modeling education should include basic learnings from social science as well as reflexivity. The current study presents an interdisciplinary course on climate modeling, called "`Hello world!` From numerical programming to complex climate models", and which we have taught 4 times (2022 - 2025). To our knowledge a course like this has not been documented in the literature before, and thus this study contributes to a generally small base of literature that explicitly treats the teaching of climate modeling.

Following design-based research practice (see Sec. 2.1), we have developed a course for high-school students that aims to teach (see Fig. 1):

- how to translate differential equations into a numerical model of a given system
- the various roles of model building in science
- the structure, function and peculiarities of GCMs
- an interdisciplinary reflection on climate model building to understand the role of models holistically

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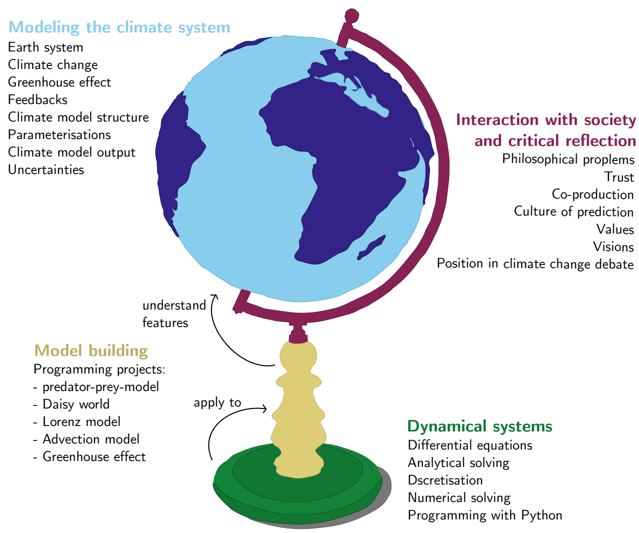

Figure 1. Content of the course, divided by the four themes or aims of the course. The colors correspond roughly to the ones used to illustrate the content analysis results in Fig. 3. For the detailed course structure, see Table A1. The sketch is based on Corona Bustamante (1860).

We have developed and taught this course at the sustainability academy ("Nachhaltigkeitsakademie" in German, short NAka). While this setup is unique (see Sec. 2), the course is geared towards advanced high school students and can certainly be adapted to a university, informal education or outreach setting. Our goals for this article are twofold: First, document the course to give inspiration and materials for others. Second, evaluate our concept to teach both modeling knowledge and its reflection at the same time. Due to the qualitative methodology employed, our findings are conceptual and subjective in that we interpret how the course resonates with the students. In particular, we evaluate scientifically whether the course triggers a reflection process for the students and what that looks like.

2 Methods

This course was developed for and taught at the NAka, a two-week summer camp in Papenburg, Germany, for especially motivated German high-school students. In total, around 100 students take part in the NAka program, and they are distributed over six courses. Hence, our course in 2024 had 17 students (mixed gender). A usual day at the NAka consists of 3.5 hours of coursework in the morning and 2.5 hours in the afternoon. In total, there are 50 hours of coursework. The courses are taught by young adults with university education in the field they are teaching and ideally with some teaching experience.

When students apply, they select 5 out of the over 50 possible course choices from around 10 similar camps taking place over the summer. The NAka, however, is the only such camp with a focus on sustainability and climate change, which may affect students' choice of the course. The NAka is organized by the non-profit organisation JGW e.V. The camp's goal is to teach a holistic understanding of climate change and sustainability, foster participants' skills, and encourage them to take responsibility and engage in society (JGW e.V., 2025).

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The NAka creates a special learning and teaching experience, where several factors need to be highlighted for our study

- While the participants are high-school students, the course is aimed to be at a Bachelor studies university level. This is to challenge students who perform well in school, but also to teach something outside their school curricula and to accommodate the fact that the previous knowledge of participants is varied (since students come from all over Germany as well as German schools abroad).
- Students attend the camp voluntarily, the course was one of their selected five, and they have been suggested for participation by their school teachers. Thus their high motivation makes for an especially fruitful learning experience, both for them and for the teachers.
- Our engagement in the NAka is a voluntary and unpaid free time activity. Our disciplinary background is in climate science, physics and numerical modeling, with university teaching experience in lectures and tutorials (see also Sec. 2.3). While the course benefits from our knowledge, and research and teaching experience, we approach it with few organisational restrictions which enables us to design the course freely.
- It's a summer camp! There are no assessments or gradings included in the course, activities need to be engaging, and we aim for an enjoyable atmosphere.

2.1 Design-based research

In developing the course, we were engaging in design-based research (see for example Assaraf and Orion (2009)). This branch of education studies simultaneously develops, tests and improves an educational module, proceeding over iterative cycles. Cohen et al. (2011b, Chp. 16.10) link it to engineering studies, where prototypes are developed, tested, and the feedback is applied to a new development round of the product. While we were loosely engaged in this practice the first two years, as we incorporated participants' feedback (see Sec. 3.2), we took the third year (in 2024) as an opportunity for a more thorough evaluation of the course concepts. The design-based research framework fits our approach because it formalises our two-fold goal of designing and researching the teaching and thereby fruitfully combines our two interlinked roles of teachers and designers. In design-based research, the "agenda of the designers is seens as a positive force rather than a threat to validity" (Hoadley and Campos, 2022). Moreover, the approach is interventionist, for example allowing "tweaking the intervention to better match the design intent mid-implementation" Hoadley and Campos (2022) rather than sticking with an ill-suited design in order to keep study conditions constant. We made use of this when improving the course in between editions.

2.2 Research questions and their assessment

For the third cycle, we set out to not only evaluate and improve the course in terms of direct feedback, but wanted to dive deeper into understanding the students' learning progress. Our goal for the course has been to teach both numerical (climate) modelling and its critical reflection. The combination of natural sciences with philosophy of science and science and technology studies (STS) (Sismondo, 2010) has been a thought-provoking and challenging experience for us. We were motivated to give

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students in the course a similar intellectual experience as well as a holistic picture of climate change modelling as a socio-scientific issue from the start (Rafolt et al., 2019). During the first two cycles, we have noted incidents that hinted at individual students undergoing a profound change of their perspectives and conceptions. Therefore, in the third cycle we wanted to study what that process looks like and whether more than single students were undergoing it. Additionally, we were interested in which modules in particular facilitated the learning process and where students faced challenges integrating modules with their thoughts. Accordingly, we formulated our research question as:

> In our interdisciplinary course on climate modeling, what does the students' learning look like and does it align with envisioned learning outcomes? What thought processes does the course trigger? Do we see evidence for change in students' thinking about climate models?

In choosing the assessment method we were guided by the following considerations.

- As time for the course is short, the course should not be interrupted by extra activities, but these should be integrated into the course flow.
- The participants should gain something from the tasks they fulfill for the assessment.
- The exercise should not feel like they are being "assessed" in school, which would entail pressure as well as an enhanced risk of the "good-subject effect" (Orne (1962); Nichols and Maner (2008), a form of participant bias), meaning that the students would be encouraged to answer what they believe we would want to see.
- Assessment products should be written down in order for us to have them documented and accessible for analysis and interpretation further on.
- The assessment exercise should take place close to the modules that we foresee to trigger thought processes. In the second cycle we attempted to get an impression of students' reflective change by asking in a survey in the end how their perceptions changed, but their answers were shallow and short. Thus, for the formal evaluation in the third cycle we opted against an assessment at the end of the course.
- We chose a method with multiple iterations so that we could have improved the approach if it had appeared unfruitful.
- Since the goal of the exercise was reflection, it should be open enough so that students can answer individually rather than having their thoughts pressed into a template.

We thus opted for the iterative direct assessment of students' perception changes in a reflective exercise. Asking students for changes in their thoughts and opinions directly demands a high level of self-reflectivity on the spot. To ease them into this task, we chose to ask first what thoughts or new ideas were going through their head after a specific module (posteriori). In a second step, they were asked to add what they had been thinking about that topic beforehand (a priori). The direct confrontation was thought to be helpful for the students' reflection, but bears the threat of increasing the "good-subject effect." For each assessment we asked:

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- a posteriori: “In relation to the material covered in the last class session, note which ideas, insights or concepts are spinning in your head now. You can do that in the form of, for example text, notes or pictures.”
- a priori: “Consider how you have thought about these concepts before.”

to address the research question. We repeated this exercise 5 times, giving each of the questions 5 minutes of time (see Table A1). After each exercise, we had a short plenum discussion, with students being asked to name and explain a point from their list, collecting them on a whiteboard, and giving others and us the chance to comment or ask questions. In this way, students could learn reflection also from each other, and we could learn from their explanations, also in order to clarify the assessment.

After the course completion, we applied inductive, open-coded content analysis (Cohen et al., 2011a) to the students’ output. The first author coded for ideas and conceptions that came up, tagged each of them according to whether they belonged in the a priori or a posteriori category as well as which assessment cycle they belonged to. To evaluate the dependence of the coding on the coder, intercoder reliability was checked. After coding was completed by the first author of this paper, the second author went through 17 randomly sampled quotations and assigned the pre-existing codes to them. Comparing the coding between the two researchers, for 15 (88%) of the quotations, the second coder assigned at least one code that fit directly one that the first coder had assigned (intercoder agreement); for one quotation, they afterwards agreed on the label of the first coder; for one quotation they assigned 4 and 3 codes, respectively, and while none of them matched, they understood each other’s reasoning. While these results indicate shared understanding between the two coders, they also highlight the interpretative nature of the coding exercise, especially when assigning many codes in total and multiple per quotation. Note that not all codes that we found form a part of our analysis and the presented figures, but we focused on those that contributed to answering our research question. Prior to the NAka, all students and/or their guardians provided their informed consent to participate in our study, which had been approved by the WUR Research Ethics Committee (approval number 2024-069). The students also all had the opportunity to offer feedback on the manuscript before submission.

A clear caveat to our approach are the various forms of participant bias. For example, in an assessment setting, participants are prone to answer according to how they think their viewpoint and ideas should have changed from our point of view. We addressed this by explaining the purpose of our study to the students and encouraged their own scientific curiosity in the reflection. In addition, the plenum discussion following the exercise provided us the opportunity to analyse their expressions in more context.

2.3 Positionality

Our position and experiences shape the knowledge that we produce as researchers (see e.g. Hausermann and Adomako (2022)). Thus it is important to make them explicitly transparent (Cohen et al., 2011b, pg. 225). In this case, our role in this research is shaped by our deep engagement and identification with the NAka project, as we have both been involved multiple years, and one of us is a former participant as well as former project leader. During each course year, the students and we build a relationship that is conducive for teaching, but also colors our approach to the students as research subjects. It may also enhance the participant bias (Nichols and Maner, 2008). In addition, we have teaching training and experience, but are by no

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means educational (research) experts. Thus, our goal with this study is not to provide an objective evaluation, but rather to showcase a course approach that has proven itself in practice. Rather than hampering the results, we think our enthusiasm and the relationships we built play a large part in the success of the course.

3 Results and discussion

The primary result of design-based research is the course itself, which we describe in Sec. 3.1. Sec. 3.2 deals with changes that occurred as we were improving the course design between iterations. The evaluation of the course in terms of students' thought process and thus the answer to our research question is given in Sec. 3.3.

3.1 Course

Table A1 gives an overview of the course schedule. It is divided broadly into two themes: the first theme is concerned with the mathematical and physical aspects of numerical modelling and its application to climate models, while the second theme reflects model building critically and discusses the development of climate models in a socio-historic context.

The first topical module introduces numerical modelling as a general method and its various applications. To motivate the relevance of numerical modeling we showcase examples from various scientific disciplines in the form of pictures, brainstorming possible subjects and their diverse goals and challenges with the students. Next, we define the modeling of dynamical systems more formally and agree on a common nomenclature. This is achieved via a student presentation showcasing the differential equation (DE) of a simple physical system. To practice the newly learned terminology for the different types of DEs and their constituents we use further examples of DEs describing dynamical systems in natural sciences.

The next module is concerned with the analytical solution of the DEs. Given the varying mathematical education of the students this is a challenging topic. Therefore, we solely rely on finding a solution by means of "good guessing". The difficulties encountered during the exercise and the fact that the analytical method is only limited to a small collection of simple systems motivate the use of numerical methods for the remainder of the course.

As the most basic discretization method for solving ordinary DEs numerically we introduce the Euler method (forward and backward). For practice we let the students solve the logarithmic spiral only using pen, paper and a calculator. Since this example was already part of the analytical exercise, the students were able to compare both methods. The important lessons are: i) the numerical method is not exact as it deviates from the analytical solution and ii) the numerical method takes much effort since many more computational steps are involved. This is why we ultimately resort to computers for automating the calculations.

Our course has no requirements on prior knowledge of programming. Therefore, we teach the basics from the ground up using a simple tutorial notebook that includes exercises. As we do not have the time for an extensive programming class we follow a learning-by-doing approach in the rest of the course and rely on more experienced students to help less experienced ones. Our choice of programming language is Python as it is easy to learn and widely used in the scientific community.

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Then, we form the basis for understanding the climate system and its numerical modelling in climate models. This is achieved via first collecting students' prior knowledge of the Earth system and their interactions in a black board diagram. Additionally, there is input on climate change, climate model structure and the uncertainties in climate modelling via student presentations to dive deeper. Climate models are explored hands-on by showing the students actual climate model code and via the IPCC Interactive Atlas (Gutiérrez et al., 2021; Iturbide et al., 2022), which illustrates real model output for different variables and scenarios. Furthermore, the students write their own program to model a simplified version of the greenhouse effect, which illustrates the usefulness of numerical simulations to study processes in the Earth system.

To further practice numerical programming and learn about model building the students work on programming projects in groups. We offer a diverse set of topics (see Table A1) related to the Earth system that highlight different aspects of dynamical systems, e.g., feedbacks and chaos, and also different technical intricacies of numerical modelling, e.g., the comparison of alternative discretization schemes for partial DEs. Half way into the programming projects we ask the students to reflect on their efforts: Why do we model? This question bridges to the second theme of the course about critical reflection of model building.

This second thematic part covers the goals underlying climate model development, issues in the interpretation of climate model results and their development as embedded in the societal context. For example, by constructing a timeline from given index cards, the students dissect the co-evolution of climate models alongside relevant historical events. The subsequent first silent and then guided discussion reflects how the historic context has influenced the field of climate science and thus how models and for example views of a global Earth were co-produced (Heymann, 2019). In another exercise, the students get to know three main motivations or visions for climate model development by assigning quotes or methods to the vision categories. These have been developed by Shackley et al. (1999); Shackley (2001); Sundberg (2009) and summarized by Proske et al. (2024) as the representative, predictive and heuristic vision. These visions put the focus on the model being a copy of the real system, providing accurate forecasts, or on being used as a tool to generate understanding, respectively. While these visions can work together, they may also lead to conflict, for example where more detailed models that are more representative become too complex to understand, thus decreasing their heuristic utility (Proske et al., 2023, 2024). Parker (2006) and Winsberg (2012) have explained some problems of climate modeling from a philosophical perspective, such as distributed epistemic agency and generative entrenchment. These texts serve as the basis for a group work where students read the texts in groups and then present them to the others in a creative format. An example of a particularly vivid display is shown in Fig. 4 and described further in Sec. 3.3. After discussing long- or outstanding issues in climate model development, we find it important to circle back to the question of why one can trust many climate model results after all. Knutti (2008a, b) has written accessible elaborations of the reasons that serve as the basis for one student pair's presentation. The course content ends with a fish bowl discussion of climate scientists' position in the climate change debates. The students are again divided in groups and get some input for a particular position they are asked to represent, ranging from disinterestedness in public discussion to activist positions. While students can use knowledge gained in the course to back up their arguments in the ensuing discussion, the topic circles back to the idea that climate models are a product of and feed back into our society.

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3.2 Course development cycles

Each of the three years that we taught the course offered an opportunity for improvement, based on our own experiences and students' feedback. After initial struggles with the analytical solving of differential equations, the basics of numerical modeling and model building seemed to always be well understood by the students. Integrating the science and technology studies (STS) content was more challenging. In the first year, we separated the numerical modeling from the STS content as a first and second thematic block, but in the following years we integrated the two approaches more. The integration serves to have the understanding of both perspectives benefit each other, with parameterisations being a key component of model formulation and reflected in the representative modeling vision, but also a basic reason for modeling uncertainties. Also, the integration allows to mix methodologies, with more discussions and text-based work in the STS part of the course. For the same purpose, we have increasingly dispersed the students' presentations throughout the course.

Design-based research is a continuous journey. From the findings of the present study and the direct feedback from the 2024 students we have again modified the next course iteration. For example, we introduced scenarios more explicitly in order to pick up students' thoughts on human "manipulation". Because students criticized too much time in plenary discussions, we used poster sessions instead of presentations and also had only two programming projects in parallel, in order to keep the need for transfer of knowledge and results between groups small.

3.3 Reflective exercise

Fig. 2 shows the themes that participants included in their reflective exercises. After inductive coding, we found that main topics correspond to topical blocks in the course program, for example model problems, visions, or the concept of a culture of prediction (Heymann et al., 2017a), and thus assigned those deductively (compare Table A1). Regarding our research question, this already shows that the learning aligns with the teaching goals. One prominent theme in the participants' responses are the different modeling visions. The understanding that there are multiple visions that may lead to conflict emerges directly from the corresponding exercise conducted in the course (see Table A1). However, two students also expressed the idea that the different visions lead to more diverse science, i.e. multiple approaches being followed. While this positive understanding was not an explicit part of the exercise, it corresponds to arguments in favour of climate model hierarchies as brought forward in the literature (Jeevanjee et al., 2017).

Another theme is that of how science works. That this theme came up is suprising to us because it was not explicitly treated in the course. Here participants viewed science as a practical job, the scientists as people, and science in general as not being objective. For example, one participant commented on the "chaotic scientific work" and elaborated that "the everyday life of science is by far not as polished as papers can make it seem [TN19, RE2]." In particular, one participant seems to have imagined themselves in the climate modeling job, asking "How many feelings of success does one have in climate modeling? [TN03, RE1]"

There are no clear misconception in the responses. However, the pronounced presence of the "scenarios and manipulation" code theme strikes a cautious note. This theme arose out of the course work with the IPCC Interactive Atlas (Gutiérrez et al.,

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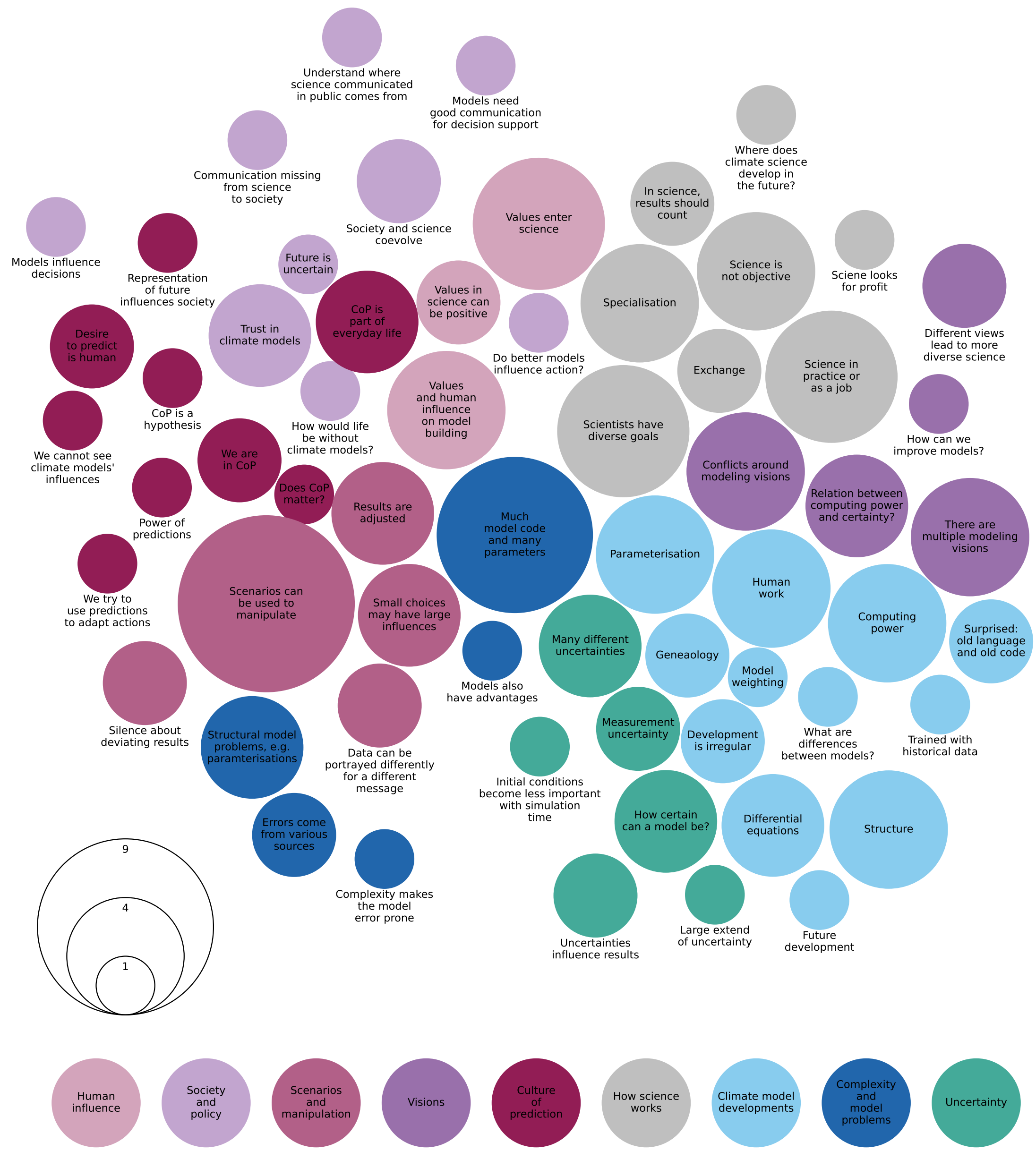

Figure 2. Overview of topics brought up in the reflective exercises, over all assessment rounds and both a posteriori and a priori answers. The codes are color-coded by themes as in Fig. 1 (red tones for “Interaction with society and critical reflection”, blue tones for “Modeling the climate system”) and the circle areas correspond to the number of times the codes were assigned.

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2021). Students were asked to think of a question to investigate with the simulation results and plotting capabilities available on the platform. In the discussion of their results, we paid particular attention to how the different time frames and climate change scenarios they used can influence the answers to their questions. Our treatment of the influence of scenario choices seems to have combined with pre-conceived ideas of manipulation to form the idea that scenarios can be or even are used to manipulate: "by choosing different scenarios one can easily manipulate humans" [TN13, RE2]. Informal conversations with students at the NAka 2025 pointed us to what these pre-conceived ideas could be about: students were sensitive to fake news and manipulative statements, seemingly because of frequent treatment of these issues in school, also due to the growth of right-wing populism in Germany. While scenarios do have a large influence that should be questioned, manipulation is not what climate science uses them for. Here we recognize an issue that science and technology studies have had to grapple with: on the one hand, from a constructivist point of view one comes to criticise the power of science and its human foundations (see for example Jasanoff (1996), and Moon and Blackman (2014) for an explanation of constructivism). On the other hand, most critics do recognise science's results as true and do not wish to imply that for example climate change is not real. This is a delicate balance to be struck (see for example Schindler (2020)). From the students' responses we saw that our balance was off and consequently took more time in the next year to introduce scenarios more rigorously.

The second part of the exercise also targeted changes in students' perceptions, as they had to describe how they thought about the mentioned topics before the course or before the last course modules. Fig. 3 displays the results of that exercise. The answers to the different rounds of the reflective exercise are combined here, because answers usually do not refer to (topics of) past modules covered in other rounds. In general, students reported less knowledge before the course and simply not having thought about some issues before (for example "I didn't know so clearly that there are also many negative feedback loops (I had only heard of the halting of the Gulf Stream before)" [TN16, RE2]) , which supports the course's goal to introduce knowledge from beyond what is present in high-school curricula. When they knew a concept from before, some students said that giving it a name makes the concept more concrete. Establishing a language to grasp concepts and talk about them is one part of what social science knowledge can do for natural scientists, as for example Remmers et al. (2025) explain. With regards to climate models, multiple students reported to have found them "unimaginable" [P3, RE1] before, but that their idea of them became more concrete. In that sense, the course allowed them to un-box climate models and build an understanding as a basis for interpretation, as students demonstrated with the exercise displayed in Fig. 4. The understanding that climate models are complex goes hand in hand with this unboxing. One students said they had been aware of complexity before, another said they had underestimated it, and more had been unaware before. Human influence was a topic that was more frequent in "a posteriori" comments, where students realised that scientific endeavours such as building or running a climate model are subject to values and human influences, again in line with the course content.

A particular insight into participants' thoughts during the course came from the questions they asked themselves during the reflective exercise. During the first exercise, one participant asked (arrow present in their notes):

> How much of climate modeling is logical and easily explainable and deducible? → How much can/could we implement in our own climate model? [TN04, RE1]

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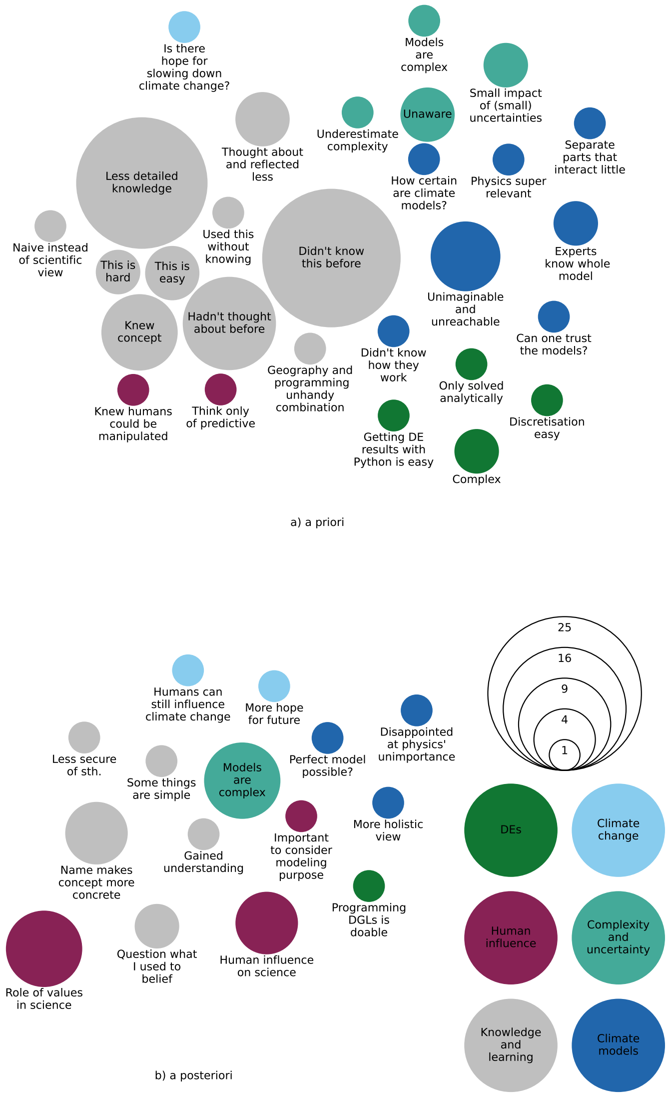

Figure 3. Codes that emerged from the content analysis of the students' reflective exercise, regarding what they answered as concepts and thoughts they had a) "a priori" the course or course module and b) "a posteriori" the course module. The codes are color-coded by themes (related to Fig. 1) and the circle areas correspond to the number of times the codes were assigned. Note that quotes could be assigned to multiple codes were they fit to multiple. The circles for "apriori" are generally smaller because students noted fewer points (for example none for differential equations (DEs)).

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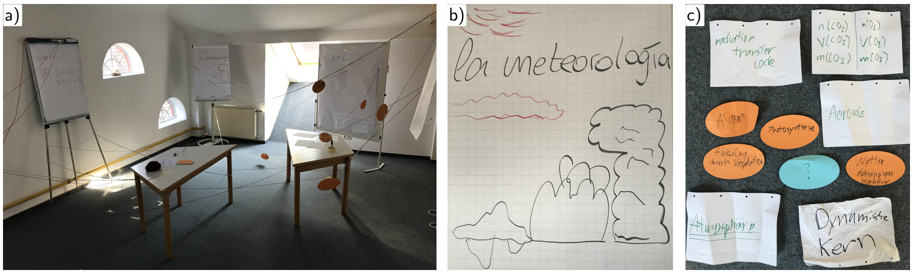

Figure 4. Students' result of the task to creatively present their text from the "Climate model problems" module. They choose to represent **a)** a climate model in the room. Climate system components are displayed on **b)** flipcharts. Interactions between them are displayed with ropes named with **c)** tags.

We interpret this as an awe of climate modeling and the complex concepts they thought would be underlying it. Others were wondering already: "How good / precise can a climate model be? [TN10, RE1]" and how this precision could be increased. One participant was increasingly doubting whether a "perfect" climate model is even possible. "How can one make projections of climate models more secure or rather more precise? → Is this possible with the current computing power and the time that one would need to spend to find possible errors? [TN06, RE2]" They added in the third round:

> Is it even possible to write a "perfect" climate model, if one is using prior data and models? → This question arises for example because of mistakes in initial computations → requires enormous amounts of data and variables [TN06, RE3]

Others took this question further, wondering whether such a model would even be useful: "What are the advantages of more precise climate models? Does that influence human action? → Aren't current statements enough? [TN10, RE3]" The course-block on the historical evolution of climate modeling brought up the question of how it will continue: "History of (climate) science extremely interesting → for me it raises the question: where are we going? How will these sciences evolve? [TN03, RE3]." These comments and questions highlight that at least for some students the course prompted a thought process on the goals and future of climate modeling.

A particularly vivid display of students' thinking about climate models emerged from the exercise on climate model problems. Three groups were asked to read different excerpts from Parker (2006) and Winsberg (2012), discuss them and present the content to the other groups, in a creative format. The group tasked with the excerpts from Winsberg (2012) decided to turn a small spare room into a climate model display. Fig. 4 shows how they used flipcharts as model components, ropes to link them, and annotated the ropes with the linking elements. For example, aerosols would be linking the atmosphere and radiation component of the model. Model components were written in different languages to represent international development distributed in time and space. They purposefully included a mistake or bug in the model (Pipitone and Easterbrook, 2012; Proske and Melsen, 2025), and the overall entanglement of the ropes served to represent the complexity of the model.

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4 Conclusions

The learning and thought processes triggered by the course are clearly visible in Fig. 2, 3 and 4. The course taught the students not only how to set up a numerical model themselves, but expanded on a reflection on climate models inspired by historical, philosophical and STS treatments. Students displayed a learning of the physical science and the reflection content together, and grew to have a multi-faceted view of climate modeling with an advanced view on climate models' challenges and problems as well as on science as a human enterprise. From the different modules we surveyed, none stood out as a particular challenge or catalyst. We found little evidence for misconceptions that students developed, and similarly no clear challenges or hurdles that arose from the course's interdisciplinary content. In a previous course edition, the reflections on the influence of values on climate model development and use were treated in the last days of the course. Back then, one participant told us that this shook up their whole belief in objective science, and that they would have liked to have more time to process this during the course. Thus, we expected protest or at least critical questions from students overwhelmed by the combination of learning differential equations at the same time as the societal influence on science (akin to the "disorienting dilemmas" studied by Feng et al. (2025)). These were missing from our results. Because these questions also did not appear during the course, we conclude that students simply were not shocked. We suspect that without students having undergone a full scientific academic education, attacking the pillars of a positivist belief in scientific truth does not in general shake them up. This may also be an indication that while students take up the knowledge easily, they do not integrate it immediately into their belief system and therefore do not show an emotional or deep-felt response.

The reflective exercise we conducted revealed topics students were debating at the time of the exercise. On the one hand, these mostly aligned closely with the course content, so it was difficult to identify students' personal thought process amidst the general course progression, and thus our contribution to that research question is limited. On the other hand, many codes of the students' answers only had one count, as students mentioned a wide potpourri of statements among each other. That each student takes away something different is of course an interesting feedback and learning for the teachers. It also confirms that the method was suited to allow for a wide range of response and gave students the freedom to detail their own thoughts (which then still were closely aligned with the course progression). One weakness of the method was that students often did not spell out the "a posteriori" when naming the "a priori" and vice versa. For example, they said climate models were unimaginable before and that only implied that it is not unimaginable afterwards anymore. The exercise did encourage students to reflect, as the nature of responses changed from content and feedback related notes to reflections with more exercise rounds. Reflective group discussions or a reflective essay may have provided more in-depth views of students' reflections.

Overall, while this study does not "validate" our course as an ideal way for interdisciplinary climate model education, it does show that there are ways to integrate modeling and social sciences already in teaching. Thus, it seems that a climate modeling course that is interdisciplinary from the start is possible, with the hope that it contributes to reflected model use and development, and an awareness of human influences on models as well as their restricted purposes. The resources developed for this course are openly available, inviting to their use and providing inspiration for other modeling courses.

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Data availability. We have shared the material that we use for the course at zenodo (Proske and Staab (2026), where this was possible without copyright limitations).

Appendix A: Course schedule

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Table A1. Course schedule detailing the modules, the methods used within and the goals worked towards, as well as the approximate time planned for each of them. The reflective exercises are underlined. Horizontal lines denote the end of a course block, which took 3:20 hours in the morning or 2:20 h in the afternoon.

Duration	Content	Method	Goal/Competences
1:30	Welcome Icebreaker Introduce the schedule Rules for the course	**Plenum** position yourself on answer scales	Establish discussion culture Get to know each other
0:30	Applications of numerical modelling. What are numerical models used for?	**Picture gallery**	Introduction and motivation Learn about subjects and goals of numerical modeling
0:10	Introduce feedback	**Feedback sandwich**	Giving and receiving feedback
0:35	Dynamical systems can be modelled	**Student presentation** "Example of a dynamical system"	Provide a first example that students are familiar with from school (e.g. pendulum)
0:30	Nomenclature around DEs	**Plenum** "Find what belongs together": DEs, state variables and parameters	Become familiar with DEs
0:30	Getting to know each other	**Energizer/game**[1]	
0:30	Introduce analytical solving	**Input**	Know process to solve simple systems analytically
1:00	Practice analytical solving	**Exercise sheet** for each student by themselves, discuss in plenum	Apply analytic solving; experience limits and frustration to motivate discretisation
1:30	Discretizing ordinary DEs	**Input and group work** logarithmic spiral	Discretize ordinary DEs yourself Numerical solutions are approximations and the results from different methods differ
3:30	Introduction to Programming	**Input** with everyone following on their computer	Understand and write simple programs yourself

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Table A2. Continuation of Table A1.

Time	Content	Method	Goal/Competences
0:30	Components of the Earth system and their interactions	**Plenum** Create diagram on the board together	The Earth system is complex Know examples for components
0:35	Climate change	**Student presentation**	
4:00	Green house effect as the physical basis for climate change	**Group work** Students write a program computing the green house effect following an exercise sheet	Translating simple physical systems into a numerical program to study them
0:40	Climate model structure	**Student presentation**	Technical structure
0:20	Climate model code	**Plenum** Open up climate model code we have access to and go through parts of it together	Realise that even with only a programming introduction, one can already read that code and understand single parts, but that the whole program is massive and difficult to comprehend
0:40	Uncertainties in climate modeling	**Student presentation**	Reasons for uncertainties in climate modeling Treatment of these uncertainties Science can generate knowledge despite uncertainties
0:20	Reflection	**Reflective exercise** Introduction of the concept and first execution	
2:00	Climate model output	**Group work** Students explore the IPCC Interactive Atlas. They are asked to think of a question that they want to investigate and prepare one Figure to share their findings with the group.	Climate model output is huge in terms of data and information Finding and answering a research question Selecting and summarizing results Presentation skills

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Table A3. Continuation of Table A1.

Time	Content	Method	Goal/Competences
5:30	Programming projects: Feedbacks Chaos Numerical techniques	**Group work** on different projects: Predator-pray-model Daisy world Lorenz model Advection model Continuation greenhouse effect	Constructing and revising a model Possibilities and limits of numerical models Evaluating models Programming practice Presentation skills
0:30	Why do we model?	**Plenum** flipchart collection	Reasons and goals of modeling Concept of adequacy for purpose (Parker, 2009)
0:40	Feedbacks	**Student presentation**	Understanding the concept so that it can be applied to the programming projects (see above)
1:20	Documentation	**Pair work** Students work in pairs on a selected topic of the course, summarizing it but also highlighting which overarching concepts their topic illustrates and how it stands in relationship to climate models	Summarizing and contextualizing in written text

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Table A4. Continuation of Table A1.

Time	Content	Method	Goal/Competences
0:20	Recap of the first half		
0:40	Parameterisations	**Student presentation**	General concept and example of aerosol cloud interactions Obstacles to strictly physical representations in climate models
1:30	Philosophical problems in climate modeling	**Think, pair, share** One example of the outcome is shown in Fig. 4	Epistemological problems that are specific to climate modeling Understanding, summarizing and presenting literature
0:40	Trust in climate models	**Student presentation**	Reasons and limits to trust in climate models
1:30	Co-evolution/Co-production	**Group work** sorting cards referring to climate model and societal developments along a timeline	Climate science as a discipline has a historical origin and baggage The coevoution with societal ideas and movements influences the working of, people in and goals for climate modeling
0:20	Reflection	**<u>Reflective exercise</u>**	
0:40	Culture of prediction	**Student presentation**	Prediction-focus of modern society Critiquing widely held beliefs
0:20	Reflection	**<u>Reflective exercise</u>**	
0:40	Values in climate modeling	**Student presentation**	Epistemic, non-epistemic and pragmatic values in climate modeling
1:00	Climate modeling visions	**Plenum** Sorting cards with actors, methods or quotes on them according to their underlying modeling vision	Climate models serve differing goals Recognize conflicts in between positions
0:20	Reflection	**<u>Reflective exercise</u>**	
1:40	Climate scientists' position in the climate change debate	**Fish bowl discussion**	Summary of modeling viewpoints Emphatically understanding and finding arguments for a given position
0:20	Reflection	**<u>Reflective exercise</u>**	
1:30	Evaluation and Feedback		

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Author contributions. UP conceptualized the research and conducted the formal analysis. MS developed the figures. UP and MS both conducted the research, developed and conducted the teaching, and wrote the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Ethical statement. Prior to the NAka, all students and/or their guardians provided their informed consent to participate in our study, which had been approved by the WUR Research Ethics Committee (approval number 2024-069).

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References

Addor, N. and Melsen, L. A.: Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models, Water Resources Research, 55, 378–390, https://doi.org/10.1029/2018WR022958, 2019.

Alves, D. S.: Two Cultures, Multiple Theoretical Perspectives: The Problem of Integration of Natural and Social Sciences in Earth System Research, International Perspectives on Global Environmental Change, 2012.

Assaraf, O. B.-Z. and Orion, N.: A Design Based Research of an Earth Systems Based Environmental Curriculum, Eurasia Journal of Mathematics, Science and Technology Education, 5, 47–62, 2009.

Babel, L.: Decision-Making in Model Construction: Unveiling Habits, Environmental Modelling and Software, 120, 14, https://doi.org/10.1016/j.envsoft.2019.07.015, 2019.

Cohen, L., Manion, L., and Morrison, K.: Coding and Content Analysis (Chapter 30), in: Research Methods in Education, Routledge, seventh edn., 2011a.

Cohen, L., Manion, L., and Morrison, K.: Research Methods in Education, Routledge, seventh edn., ISBN 978-0-415-58336-7, 2011b.

Corona Bustamante, J.: Globe Terrestre En Relief [Document Cartographique], https://catalogue.bnf.fr/ark:/12148/cb40673676k, 1860.

Easterbrook, S. M.: Computing the Climate: How We Know What We Know About Climate Change, Cambridge University Press, Cambridge, ISBN 978-1-107-13348-8, https://doi.org/10.1017/9781316459768, 2023.

Edwards, P. N.: Representing the Global Atmosphere, in: Changing the Atmosphere, The MIT Press, ISBN 978-0-262-27981-9, https://doi.org/10.7551/mitpress/1789.003.0005, 2001.

Feng, X., Sundman, J., Aarnio, H., Taka, M., Keskinen, M., and Varis, O.: Towards Transformative Learning: Students' Disorienting Dilemmas and Coping Strategies in Interdisci, European Journal of Engineering Education, 50, 2025.

Gettelman, A. and Rood, R. B.: Demystifying Climate Models, Springer Berlin Heidelberg, New York, NY, ISBN 978-3-662-48957-4, 2016.

Gutiérrez, J. M., Jones, R. G., Narisma, G. T., Alves, L. M., Amjad, M., Gorodetskaya, I. V., Grose, M., Klutse, N. A. B., Krakovska, S., Li, J., Martínez-Castro, D., Mearns, L. O., Mernild, S. H., Ngo-Duc, T., van den Hurk, B., and Yoon, J.-H.: Atlas, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.021, 2021.

Hausermann, H. and Adomako, J.: Positionality, 'the Field,' and Implications for Knowledge Production and Research Ethics in Land Ch, Journal of Land Use Science, 2022.

Heymann, M.: Constructing Evidence and Trust: How Did Climate Scientists' Confidence in Their Models and Simulations Emerge?, in: The Social Life of Climate Change Models, edited by Skrydstrup, M. and Hastrup, K., pp. 213–234, Taylor & Francis, ISBN 0-415-62858-X, 2013.

Heymann, M.: The Climate Change Dilemma: Big Science, the Globalizing of Climate and the Loss of the Human Scale, Regional Environmental Change, 19, 1549–1560, https://doi.org/10.1007/s10113-018-1373-z, 2019.

Heymann, M.: Knowledge Production with Climate Models: On the Power of a "Weak" Type of Knowledge, in: Weak Knowledge: Forms, Functions, and Dynamics, pp. 321–349, Campus Verlag, Frankfurt, ISBN 978-3-593-50977-8, 2020.

Heymann, M., Gramelsberger, G., and Mahony, M., eds.: Cultures of Prediction in Atmospheric and Climate Science: Epistemic and Cultural Shifts in Computer-Based Modelling and Simulation, Routledge Environmental Humanities Series, Routledge, Taylor & Francis Group, London New York, NY, ISBN 978-0-367-15229-1 978-1-138-22298-4, 2017a.

Heymann, M., Gramelsberger, G., and Mahony, M.: Key Characteristics of Cultures of Prediction, in: Cultures of Prediction in Atmospheric and Climate Science, pp. 18–41, Routledge, Taylor & Francis Group, ISBN 978-0-262-63219-5, 2017b.

Hoadley, C. and Campos, F. C.: Design-Based Research: What It Is and Why It Matters to Studying Online Learning, Educational Psychologist, 57, 207–220, https://doi.org/10.1080/00461520.2022.2079128, 2022.

Hulme, M.: Geographical Work at the Boundaries of Climate Change: Boundary Crossings, Transactions of the Institute of British Geographers, 33, 5–11, https://doi.org/10.1111/j.1475-5661.2007.00289.x, 2008.

Iturbide, M., Fernández, J., Gutiérrez, J. M., Pirani, A., Huard, D., Al Khourdajie, A., Baño-Medina, J., Bedia, J., Casanueva, A., Cimadevilla, E., Cofiño, A. S., De Felice, M., Diez-Sierra, J., García-Díez, M., Goldie, J., Herrera, D. A., Herrera, S., Manzanas, R., Milovac, J., Radhakrishnan, A., San-Martín, D., Spinuso, A., Thyng, K. M., Trenham, C., and Yelekçi, Ö.: Implementation of FAIR Principles in the IPCC: The WGI AR6 Atlas Repository, Scientific Data, 9, 629, https://doi.org/10.1038/s41597-022-01739-y, 2022.

Jasanoff, S.: Is Science Socially Constructed—And Can It Still Inform Public Policy?, Science and Engineering Ethics, 2, 263–276, https://doi.org/10.1007/BF02583913, 1996.

Jeevanjee, N., Hassanzadeh, P., Hill, S., and Sheshadri, A.: A Perspective on Climate Model Hierarchies, Journal of Advances in Modeling Earth Systems, 9, 1760–1771, https://doi.org/10.1002/2017MS001038, 2017.

JGW e.V.: NachhaltigkeitsAkademie, 2025.

Knutti, R.: Hotter or Not? Should We Believe Model Predictions of Future Climate Change?, Significance, 5, 159–162, https://doi.org/10.1111/j.1740-9713.2008.00320.x, 2008a.

Knutti, R.: Should We Believe Model Predictions of Future Climate Change?, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366, 4647–4664, https://doi.org/10.1098/rsta.2008.0169, 2008b.

Mahony, M. and Hulme, M.: Modelling and the Nation: Institutionalising Climate Prediction in the UK, 1988–92, Minerva, 54, 445–470, https://doi.org/10.1007/s11024-016-9302-0, 2016.

Mahony, M. and Hulme, M.: Epistemic Geographies of Climate Change: Science, Space and Politics, Progress in Human Geography, 42, 395–424, https://doi.org/10.1177/0309132516681485, 2018.

Melsen, L. A.: It Takes a Village to Run a Model—The Social Practices of Hydrological Modeling, Water Resources Research, 58, https://doi.org/10.1029/2021WR030600, 2022.

Moon, K. and Blackman, D.: A Guide to Understanding Social Science Research for Natural Scientists, Conservation Biology, 28, 1167–1177, https://doi.org/10.1111/cobi.12326, 2014.

Nichols, A. L. and Maner, J. K.: The Good-Subject Effect: Investigating Participant Demand Characteristics, The Journal of General Psychology, 135, 151–166, https://doi.org/10.3200/GENP.135.2.151-166, 2008.

Orne, M. T.: On the Social Psychology of the Psychological Experiment: With Particular Reference to Demand Characteristics and Their Implications, American Psychologist, 17, https://doi.org/10.1037/h0043424, 1962.

Parker, W. S.: Computer Modeling in Climate Science: Experiment, Explanation, Pluralism, Ph.D. thesis, University of Pittsburgh, 2003.

Parker, W. S.: Understanding Pluralism in Climate Modeling, Foundations of Science, 11, 349–368, https://doi.org/10.1007/s10699-005-3196-x, 2006.

Parker, W. S.: Confirmation and Adequacy-for-Purpose in Climate Modelling, Aristotelian Society Supplementary Volume, 83, 233–249, https://doi.org/10.1111/j.1467-8349.2009.00180.x, 2009.

Pipitone, J. and Easterbrook, S.: Assessing Climate Model Software Quality: A Defect Density Analysis of Three Models, Geosci. Model Dev., https://doi.org/10.5194/gmd-5-1009-2012, 2012.

https://doi.org/10.5194/egusphere-2025-6313
Preprint. Discussion started: 6 January 2026

Proske, U. and Melsen, L. A.: How Climate Model Developers Deal With Bugs, Earth's Future, 13, e2025EF006 318, https://doi.org/10.1029/2025EF006318, 2025.

Proske, U. and Staab, M.: Teaching Materials for "Hello World! Teaching an Interdisciplinary Understanding of Climate Modelling", zenodo, https://doi.org/10.5281/zenodo.17791563, 2026.

Proske, U., Ferrachat, S., Klampt, S., Abeling, M., and Lohmann, U.: Addressing Complexity in Global Aerosol Climate Model Cloud Microphysics, Journal of Advances in Modeling Earth Systems, 15, e2022MS003 571, https://doi.org/10.1029/2022MS003571, 2023.

Proske, U., Ferrachat, S., and Lohmann, U.: Developing a Climatological Simplification of Aerosols to Enter the Cloud Microphysics of a Global Climate Model, Atmospheric Chemistry and Physics, 24, 5907–5933, https://doi.org/10.5194/acp-24-5907-2024, 2024.

Rafolt, S., Kapelari, S., and Kremer, K.: Kritisches Denken im naturwissenschaftlichen Unterricht – Synergiemodell, Problemlage und Desiderata, Zeitschrift für Didaktik der Naturwissenschaften, 25, 2019.

Remmers, J. O. E., ter Horst, R., Nabavi, E., Proske, U., Teuling, A. J., Vos, J., and Melsen, L. A.: HESS Opinions: Reflecting and Acting on the Social Aspects of Modelling, EGUsphere, pp. 1–19, https://doi.org/10.5194/egusphere-2025-673, 2025.

Schindler, S.: The Task of Critique in Times of Post-Truth Politics, Review of International Studies, 46, 376–394, https://doi.org/10.1017/S0260210520000091, 2020.

Shackley, S.: Epistemic Lifestyles in Climate Change Modelling, in: Changing the Atmosphere, MIT Press, ISBN 978-0-262-63219-5, 2001.

Shackley, S., Young, P., Parkinson, S., and Wynne, B.: Uncertainty, Complexity and Concepts of Good Science in Climate Change Modelling: Are GCMs the Best Tools?, Climatic Change, 38, 159–205, https://doi.org/10.1023/A:1005310109968, 1998.

Shackley, S., Risbey, J., Stone, P., and Wynne, B.: Adjusting to Policy Expectations in Climate Change Modeling, Climatic Change, 43, 413–454, https://doi.org/10.1023/A:1005474102591, 1999.

Sismondo, S.: An Introduction to Science and Technology Studies, Wiley-Blackwell, Chichester, second edition edn., ISBN 978-1-4051-8765-7, 2010.

Sundberg, M.: Parameterizations as Boundary Objects on the Climate Arena, Social Studies of Science, 37, 473–488, https://doi.org/10.1177/0306312706075330, 2007.

Sundberg, M.: The Everyday World of Simulation Modeling: The Development of Parameterizations in Meteorology, Science, Technology, & Human Values, 34, 162–181, https://doi.org/10.1177/0162243907310215, 2009.

Undorf, S., Pulkkinen, K., Wikman-Svahn, P., and Bender, F. A.-M.: How Do Value-Judgements Enter Model-Based Assessments of Climate Sensitivity?, Climatic Change, 174, 19, https://doi.org/10.1007/s10584-022-03435-7, 2022.

Ward, Z. B.: On Value-Laden Science, Studies in History and Philosophy of Science Part A, 85, 54–62, https://doi.org/10.1016/j.shpsa.2020.09.006, 2021.

Winsberg, E.: Values and Uncertainties in the Predictions of Global Climate Models, Kennedy Institute of Ethics Journal, 22, 111–137, https://doi.org/10.1353/ken.2012.0008, 2012.