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A Learner-Centered Approach to Teaching the Physics of Climate during the COVID-19 Pandemic

ABSTRACT/ZUSAMMENFASSUNG

Das Klima der Erde ist im Wandel: die Geschwindigkeit und Richtung dieses Wandels werden angetrieben durch die anthropogenen Treibhausgasemissionen in die Atmosphäre und die Auswirkungen von Klima-Feedbacks. Der M.Sc.-Kurs “Klimaphysik” an der Universität Heidelberg soll Studierenden ein vertieftes Verständnis des Klimasystems vermitteln sowie Ihnen die Methoden zu dessen Untersuchung nahebringen. Im Sommersemester 2020 wurde dieser Kurs von einem Lehrteam angeboten, bestehend aus drei Dozierenden (inklusive der Autorin) und zwei Tutor:innen. Die Autorin war für die Entwicklung lernendenzentrierter Lehr-Lern-Aktivitäten der Studierenden verantwortlich sowie dafür, die Möglichkeit eines gemeinsamen, reflektierten und wissenschaftlichen Workflow zu schaffen. Dies führte zu der Aufnahme von Klimamodellen als einem neuen Thema in den Kurs und der Umgestaltung der wöchentlichen Übungsaufgaben mit Hinblick auf die neu formulierten Ziele. Der neugestaltete Kurs beinhaltete nun ein übergreifendes Klimamodellierungs-Experiment, in welchem die Rotationsrate der Erde (umgekehrt korrelierend mit der Tageslänge) variiert wurde von 0,25 bis hin zu 2-mal der derzeitigen Rotationsrate. Zunächst wurde festgestellt, dass über fundamentale Gleichungen keine Vorhersagen für Veränderungen in der atmosphärischen Zirkulation gemacht werden können. Auf dieser Basis formulierten Studierende Hypothesen zu Klimafolgen, führten Modellierungs-Experimente durch und analysierten und diskutierten ihre Ergebnisse. Aufgrund der COVID19-Pandemie wurde der Kurs komplett online abgehalten, was in Bezug auf Kommunikation, Ausstattung und die zusätzliche Arbeitsbelastung sowohl für das Team der Lehrenden als auch für die Studierenden eine große Herausforderung darstellte. Dennoch absolvierten mehr als 35 Teilnehmer:innen den Kurs. Insgesamt erhöhte der lernendenzentrierte Ansatz aufgrund der Kombination der Allgemeinsituation gerade zu Beginn der Pandemie und der starken Ungewissheit in Bezug auf die technische Ausstattung die Vorbereitungszeit der Dozierenden und Tutor:innen. Auch die Studierenden erforderten aufgrund ihrer hohen Motivation mehr Aufmerksamkeit während des gesamten Kurses und das technische Setup der Klima-Modellierung führte wiederholt zu der Notwendigkeit, auch kurzfristig Veränderungen an den geplanten Experimenten vorzunehmen. Dieser Artikel dokumentiert den Kursaufbau und die Anwendung eines konstruktivistischen Lernkonzepts insbesondere in Bezug auf die während des Kurses auftretenden Herausforderungen. Die Lernziele konnten nicht so erfasst und beurteilt werden, dass ein quantitativer Vergleich mit traditionelleren, hausaufgabenbasierten Lehrmethoden möglich geworden wäre; dennoch zeigten sowohl die Abschlussarbeiten als auch die studentischen Präsentationen ein hohes Maß an Verständnis für die Dynamik, Komplexität und Strukturen innerhalb des Klimasystems.

Schlagworte: Aktivierung – Klimawandel – Klimamodellierung – Online-Lehre – Projektbasiertes Lernen

Earth's climate is changing, and the pace and direction of this change are driven by the increasing anthropogenic greenhouse gas emissions into the atmosphere and the action of Earth system feedbacks. The M.Sc. course 'Physics of Climate' at Heidelberg University aims to provide students with an advanced understanding of the climate system and the methods to study it. In the summer term 2020, I co-taught this course in a team with two other lecturers and two tutors. My contribution was structured to emphasize the learners' actions and for the students to develop a connected, reflected, scientific workflow. This led to the introduction of climate models as a new topic and we enhanced the weekly exercises towards that goal. In class, we designed an overarching climate modeling experiment in which the rotation rate of the Earth (inversely related to the day length) was varied from 0.25 times the present rotation rate to 2 times. We first established that fundamental equations do not allow us to predict the changes in atmospheric circulation. Therefore, students formed hypotheses on climate impacts, performed the model experiments, and analyzed and discussed the results. Due to the COVID-19 pandemic, the course was taught exclusively online. This resulted in challenges regarding communication, equipment, and the additional workload for the teaching team as well as for the students. More than thirty-five participants successfully completed the course. Overall, the learner-centered approach increased the preparation time for the lecturer and tutors. This was due to the combination of the general situation early on in the pandemic and technical unknowns. The high degree of motivation observable from the students also required constant attention, while the technical setup of the climate model required some adjustments to the planned experiments further into the course. This paper documents the course design and execution and how we addressed the challenges following a constructivist approach to learning. The learning outcomes were not assessed in a way that would allow a quantitative comparison to traditional "homework-based" teaching. Nevertheless, the student papers and presentations highlight the high level of understanding of the dynamics, complexity, and structures in the climate system that students achieved.

Keywords: climate change – climate modeling – online teaching – project-based learning – student activation

Introduction

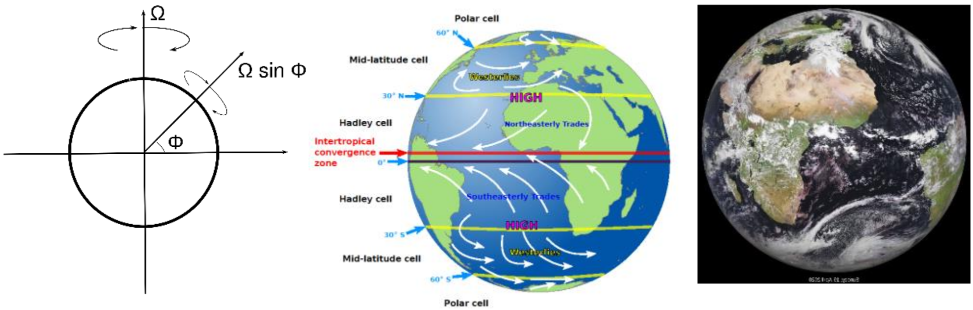
The observed warming over the last century is mostly due to anthropogenic changes to the composition of the atmosphere and can be explained based on fundamental laws of physics (IPCC 2013; Peixoto & Oort 1991). 'The Physics of Climate' (POC) is a core course offered regularly in the Environmental Physics specialization within the teaching program of the Department of Physics at Heidelberg University (Heidelberg University 2018). It is generally taught by two lecturers. Objectives, content, and format of the course aim to equip students with an advanced understanding of the climate system and methods to study the system (excerpt in the appendix). I co-taught this class with two colleagues and two tutors. Due to the development of the pandemic, all lectures and the tutorials were, in the end, held virtually and recorded for those who could not attend.

Research into the teaching of science has shown that learning can be expected to improve under teaching formats that part with traditional frontal lectures and monologues (WIEMAN 2017). At the same time, solving complex physics problems requires a variety of skills (ADAMS & WIEMAN 2015) that should be developed at university. The curriculum and teaching formats in Physics at Heidelberg University contain some active learning elements in the form of weekly assignments to be tackled in groups of up to three students. However, feedback to the assignments is often not individual, and the students cannot choose topics. Project work putting the learner's questions and individual approach into the center has so far not been adopted as a teaching tool. In the POC course, weekly assignments had previously been targeting literature reviews and analytical calculations.

The modification to the teaching program of the POC course aimed to enhance the student motivation and learning outcomes. Project work highlighting key scientific challenges through research-based teaching (MIEG & LEHMANN 2018; TREMP 2020) was therefore integrated in the lecture plan. In particular, students were expected to formulate and test hypotheses on large-scale impacts of changing a fundamental parameter in Earth's orbit: the planetary rotation rate Ω (Fig. 1).

The course content traditionally provides an overview of the physics of the climate system (PEIXOTO & OORT 1991; HARTMANN 2016; MARSHALL & PLUMB 2007). Here, it was extended to introduce climate models (STOCKER 2011; MCGUFFIE & HENDERSON-SELLERS 2014). The segment documented here comprises eight lectures and ten assignments over the course of fifteen weeks. Following a constructivist approach to learning (DECI & RYAN 2008), students were therefore expected to engage and experiment actively with tools for the study of the climate system. A working hypothesis for the author was that including hands-on work, experimentation, and regular progress discussions in the teaching process would facilitate deeper learning and furthermore demystify the concepts and results of climate models. Furthermore, project work was expected to increase the motivation and integration of students during a time of social distancing. An overview of the course, including the segment described here, is given in a table in the appendix.

The course format and the changes during the summer term of 2020, including modeling tasks, project work and online teaching, are outlined in Section 2. This section provides the basis for an assessment of the student group tasks, cross-group interactions from the teacher's perspective, and the assessment of the course by the students (Section 3). In Section 4, I summarize take-away points from this teaching experiment and highlight some of the intrinsic challenges of this format.



(a) Planetary rotation rate Ω and planetary vorticity at latitude Φ

(b) Global circulation modified from Kaidor (2013)

(c) © EUMETSAT 2020: satellite image for 2020/04/19 (https://pics.eu-metsat.int/viewer/in-dex.html)

Figure 1
Students conducted climate-modeling projects to assess the impact of changing Earth's rotation Ω on planetary climate (a). The planetary vorticity Ω sin φ, where φ is the latitude angle, features prominently in fundamental equations of planetary circulation, and influences the global circulation (b) that is visible in the cloud structures on satellite images (c).

Methods and Implementation

The Physics of Climate II

The M.Sc. course 'Physics of Climate' is part of the curriculum in Environmental Physics at Heidelberg University. Since at least the 2000s, its contents have covered planetary and Earth system evolution, atmospheric dynamics and the current state of the climate and projections (Part I), as well as the role of Earth's major compartments: atmosphere, ocean, cryosphere, biosphere, carbon and hydrological cycle (Part II, summer term). Relevant textbooks in this context are MARSHALL & PLUMB 2007, ROEDEL & WAGNER 2017, HARTMANN 2016, and, of course, the classic book by PEIXOTO & OORT 1991. A prerequisite for the course is the participation in the introductory lecture on Environmental Physics as part of B.Sc. or M.Sc. studies in Physics. The contents of this course have evolved and at present (2019/2020) include the foundation in fluid dynamics, climate, climate change, atmospheric and oceanic dynamics, paleoclimate and isotope tools in addition to other topics (HEIDELBERG UNIVERSITY 2018).

The learning objectives for the Physics of Climate II course in the summer term 2020 were that students after the course could (i) sketch the role of each compartment in the climate system in the global energy balance, (ii) describe climate models as scientific tools and perform climate model experiments, (iii) assess model output and meteorological observations, and (iv) describe the Earth's carbon cycle and the role of anthropogenic emissions. The teaching activities were a lecture (90min.), in virtual presence, preceded by a discussion of the previous week's exercises (45min.). All lectures were recorded and put on a Moodle page accessible to the class. In addition, we used forums (on Moodle), interactive questionnaires for feedback and brainstorming (e.g. AnswerGarden), and spreadsheets (Cryptpad.fr) to coordinate the modeling projects.

Modifications due to COVID-19

Due to the COVID-19 pandemic, classes had to be converted to online teaching. Furthermore, the content of other classes in the Environmental Physics program has developed to cover some of the topics of the POC class. The teaching team therefore decided to adjust course content and expand on climate modeling as a timely and relevant topic. As activating elements for the online-only teaching, we chose new programming exercises and a modeling project to enhance soft- and hard-skill development. To balance the additional workload of the weekly tutorials with the new programming-related exercises, two tutors were added to the teaching team.

For the first time, a pre-registration procedure for the lecture was introduced to respect the participant limit for the online meeting system (HeiConf). In total, 44 students signed up. The lecture had originally been planned with the expectation that the class would be able to use the computing infrastructure of the Department (CIP-Pool). This was not possible due to the pandemic, and infrastructure was improvised out of the author's research group.

The climate modeling activities were based on the Planet Simulator (FRAEDRICH et al. 2005), a simplified climate model that was explicitly designed for teaching and research at Hamburg University (FRAEDRICH et al. 2005; FRAEDRICH 2012). Fig. 2a below shows the model's run screen that allows one to inspect aspects of the circulation during the simulation. The model's complex dynamics make it a relevant tool for studying the dynamics of the atmosphere, and its efficient implementation allows one to take advantage of personal computers in UNIX/Linux environments. The model itself is easy to run: with moderate knowledge and the instructions provided, all students that tried to were able to set up simulations in less than one hour. This does not apply to the post-processing component, which proved to be more difficult to give standardized instructions for.

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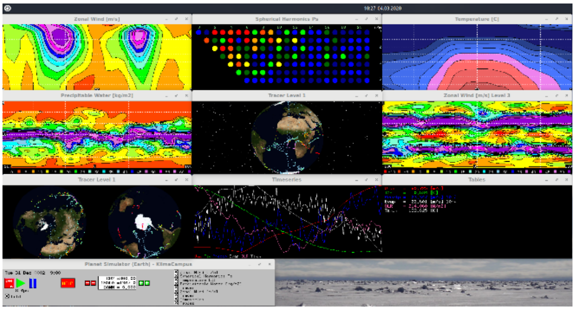

Figure 2a
The Planet Simulator runscreen showing details of the computation (spherical harmonics) and the atmospheric circulation (zonal winds, temperature, precipitable water, tracers).

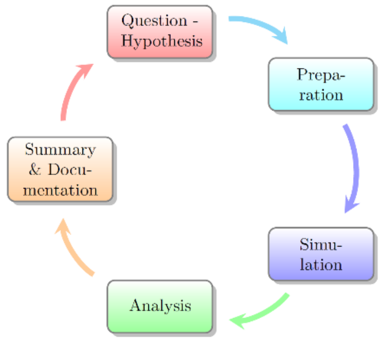

Figure 2b
(b) The circle of modeling covered in the student projects. Scientific inquiry with a question or a hypothesis (top). It proceeds through experimentation, simulation (here: with a climate model), assessment of the outcome, to end in a summary and documentation – the basis for further knowledge generation.

The Climate Modeling Project

The climate modeling project (Weeks 7-15, Table 2 in the appendix) was aimed at familiarizing students directly with the content of the lectures on atmospheric dynamics. The overarching question for the class-wide experiment was ‘What is the impact of changing Ω on planetary climate?’ Earth’s rotation has a profound effect on planetary climate, but its precise impact on the circulation cannot be categorized from an inspection of the fundamental equations due to the dimensionality and nonlinearity of the system (PEIXOTO & OORT 1991). Students were therefore encouraged to consider the problem and formulate hypotheses (Table 1 below). They then were encouraged and given instructions to install the climate model, design and set up simulations under changing day lengths, and to investigate the results based on approaches introduced in class through reference solutions (technical difficulty 1/2), or customized solutions (difficulty 3). To keep the computational load for each group low, and to enhance the interactions in the group and encourage critical thinking, two options for the exercise sheets of Weeks 8 and 9 were given. Groups who preferred not to, or could not, run simulations were given tasks relating to the theoretical background, while groups who were able to run the models first set them up and then validated the output. One group had access to our non-teaching-related computing infrastructure, ran one set of simulations for all rotation rates, and hence provided a reference dataset. In total, after Week 9, the model ensemble covered rotation rates from .2×Ω to 2×Ω. Students shared this output and the analysis code through Moodle forums and discussed their plans, results, and insights in class and in the written summary.

	What is the impact of changing Ω on planetary climate, specifically …	**Technical difficulty**
H1	…on global mean temperature and precipitation?	1
H2	…on regional precipitation (variability)?	1
H3	…on regional surface temperature (variability)?	1
H4	…on the equator-to-pole temperature gradient at the surface, and at the tropopause?	1
H5	…on the land-sea-thermal contrast?	1
H6	…on the zonal velocities of the atmospheric flow?	1
H7	…on the equilibrium climate sensitivity?	2
H8	…on the frequency of daily precipitation extremes?	2
H9	…on the frequency of daily temperature extremes?	2
H10	…on the hydrological sensitivity?	2
H11	…on the planetary energy balance?	2
H12	…on the seasonality of temperature?	2
H13	…on the spectrum of temperature variability?	2
H14	…on the extent of the Hadley circulation?	3
H15	…on the midl-latitude rossby wave number?	3
H16	…on the position of the NH subtropical jet?	3
H17	…on the position of the SH subtropical jet?	3
H18	…on the vorticity and divergence of the atmosphere?	3
H19	…on the Walker circulation?	3

Table 1
Working hypotheses for the student projects: what is the impact of changes to the rotation rate of the Earth, Ω, on planetary climate, specifically …? Technical difficulty here ranges from 1 (low, code required was already covered in exercises) to 3 (high, extended programming knowledge required).

Results

Class Organization

The modeling project relied on the individual hardware, a fair distribution of the simulation workload, and effective coordination. In Week 8, all groups declared in an online spreadsheet which experiments they would run and which simulation output they thought they would need for their analysis. This sheet was later used as a reference and updated regularly and independently. Within each group of up to three people, coordination and meeting organization for coursework was informal and, when polled, no preferred solution could be identified. In addition, I organized breakout sessions in class (Week 9) that brought together groups working on hypotheses that required similar output (e.g., 3D fields of the atmosphere, or 2D fields of the land surface) and worked on similar analyses. This 'data request' allowed us to standardize a post-processing script for the simulation output that facilitated the exchange of data between groups. These post-processed files were shared between groups via the university's online storage system ('heiBOX'). This fostered a sense of community in the student body, which could have contributed to motivation and general well-being.

Student Learning Activities

The student project work was built up over time (see Appendix for overview table). All students were engaged in the preparation, processing, discussion and presentation of their project, investigating their individual questions. They learned programming and quantitative data analysis (new for some) and discussed atmospheric and climate dynamics in class, assignments, and their project handout (a short report of five pages). They also presented their results and insights in a brief video. In the following paragraphs, I provide two examples that illustrate the range of actions across the student group and deduce what students learned.

Example 1: Impact of Changing Ω on Surface Temperature (H3)
Group 'HeisenBug' looked into the impact of the changing rotation rate Ω on surface temperature (H8). In the initial stage, they hypothesized that the Coriolis force, which increases with the rotation rate, impacted the efficiency of the poleward heat transport. Therefore, they stated that surface temperatures should decrease at the poles and increase at the equator due to a reduction of the transport of sensible and latent heat to the poles. Conversely, they expected warming for slower rotation rates. This group did not set up simulations and used data from five other groups to analyze surface temperature patterns.

Their results showed that for $\Omega=0.5x\Omega_0$, the planet cools (Fig. 3, left), whereas for $\Omega=2x\Omega_0$, the planet warms (Fig. 3, right). For different rotation rates, they also observed changing contributions from the Southern and Northern hemisphere, and a diverging response of temperature variability over land and ocean. They compared this to literature (KUHN, WALKER & MARSHALL 1989) and to the results of other groups and found their initially formed hypothesis not contradicted.

Takeaway: The combination of frontal/centrally given information with student projects allowed the students to successfully apply the scientific method of inquiry. Guided by the weekly assignments, they gradually developed their experiments, analyses, and documentation and familiarized themselves with scientific literature and the importance of reproducibility in the natural sciences.

Example 2: The Impact of Changing Ω on the Planetary Energy Balance (H11)

The Equilibrium Climate Sensitivity (ECS) is defined as the total change in global mean surface temperature after a quick doubling of the atmospheric CO_2 concentrations (IPCC 2013; PALAEOSENS PROJEKT MEMBERS 2012, GREGORY et. al. 2004). This value depends on the model, its configuration (resolution and parameterizations), and the active feedbacks it considers. The group 'Meefrange' looked into the question whether ECS would change with the rotation rate (Fig. 4) in PLASIM. Their initial hypothesis was that ECS should not depend on Earth's rotation rate since global energy balance should not depend on the rotation rate. This group used the ensemble created by the others as 'reference' with preindustrial CO_2 concentrations (280ppm) and set up simulations with 560ppm. For slower than present-day rotation rates, they found roughly constant values around the value of 6K. For higher than present-day rates, they observed a decrease. This is a realistic value, as e.g. ANGELONI, PALAZZI & von HARDENBERG (2020) find an ECS for a similar configuration of PlaSim (T21, mixed-layer ocean) of 6.23K. The group then looked at sea-ice cover and found that it also remains constant for rotation rates faster than today. They therefore attributed some of this change in ECS to ice-albedo feedbacks and concluded that their hypothesis was contradicted as they had not taken into account that feedback processes would play a large role in setting global mean temperature and therefore modulate the effect of the dominating ice-albedo effect in setting ECS.

Take-Away: This group, too, went through the process of hypothesis-experimentation-evaluation with the climate modeling experiments. Including peer-review on the project documentation (via a Moodle forum as a weekly assignment) allowed the lecturer to discuss the process and importance of peer review and peer-reviewed literature. Many of the students afterwards started to explore the general literature on the subject voluntarily and used additional literature in the discussion of their findings. This new information, together with the regular discussions in class and weekly feedback on the results, allowed the group to incorporate further variables in the assessment, which led to the recognition that the initial working hypothesis was contradicted.

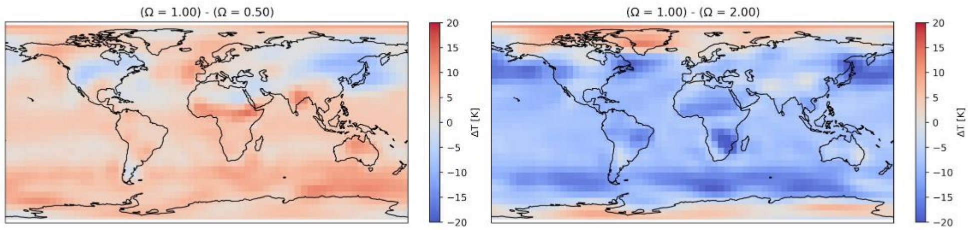

Figure 3
Comparison of lower (left) and higher (right) to present-day surface temperature (results provided by the group 'HeisenBug', Athulya Babu and Cornelia Jäschke).

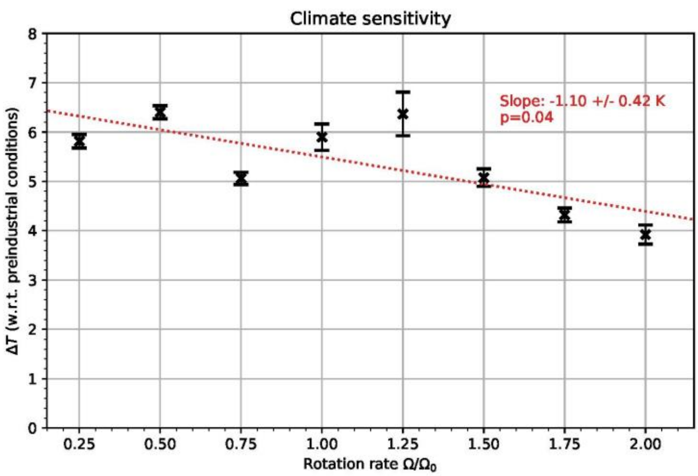

Figure 4
Estimated warming for a doubling of CO_2 concentrations under changing rotation rate (results of the group 'Meefrange', Lorenz Feineis and Oliver Mehling).

Qualitative and Quantitative Evaluation

The above examples document that students successfully learned during the course. Project assignments are, however, also stressful and somewhat unpredictable when coupled with research-based teaching, as was the general COVID-19 situation. To identify shortcomings and potentials, the lecturers therefore asked students for feedback. Three levels of feedback were taken into account: individual, via feedback forms on Moodle, and through the student body evaluation sheets (also anonymous). The formal evaluation of the faculty by the student body took place in week 14. Results for this were inconclusive, as only a few (8) students took part. In the following, the Moodle questionnaire is considered, which more students replied to.

The feedback forms in Moodle were aimed at assessing the efficacy of the teaching methods and at identifying deficits in the teaching methods. They were given to the students in Week 15, prior to the final lecture. 11 students answered three questions: (i) What did you like about the POC2 lecture? (ii) What surprised you? (iii) What would you have liked to hear more about? Answers ranged from short statements of one to two words to more than 500 words for one student. In response to (i), students highlighted they liked the group work and projects (6x), the interaction and discussion (6x), the motivation and enthusiasm of tutors/lecturers (3x), the content (5x), the research perspective as thesis preparation (3x) and the relevance for climate change (2x). Students stated they were surprised (ii) by the workload (3x), the large range of topics (2x), the simulation results (2x), the Earth system's complexity (2x) and future climate change prospects (2x), and finally that the Earth's rotation rate had changed in the past (1x). When asked what students would have liked to hear more about, the students stated that the course was 'good as is' (2x), details on the models (2x) and climate mitigation (2x), paleoclimate and proxies (2x), circulations in atmosphere and ocean (1x), and a programming course (1x). In retrospect, these questions could be rephrased as 'What supported my learning during this course? What was the greatest revelation to me? What surprised me and why? The process of learning could have further benefitted from …'.

Discussion and Conclusions

The added value of including a modeling project in teaching the physics of climate is hard to estimate based on the available data. The results of the modeling projects, as exemplified for the two groups were, however, strongly encouraging. Students identified deeply with 'their' research questions and were engaged throughout the course. On the other hand, the diverse background of the class and the necessary adjustments throughout the course timeline due to COVID and technical challenges led to some frustration. It seems possible that the elements of project-centered teaching and the flexibility of the pathways involved could have contributed to a high workload for students. In some cases, there appeared to be compound effects through the global health situation, isolation, technical difficulties, and high intrinsic motivation. While we did not record student workload systematically, we estimated that the project work and presentation increased the workload compared to a course without the projects. Exceptionally, the course participants were then given five credit points (5CP=150 hours of workload) instead of 4CP.

Deep learning and high motivation were evident in the students' final submissions for the modeling projects. These were, without any exception, of high quality in form and content. By conducting this kind of overarching modeling project to investigate the complex behavior of the climate system, the class was brought together and engaged systematically in the scientific process. Over time, each group appreciated the results of others as patterns emerged from the different analyses. Together, we came to the conclusion that global mean temperature was strongly modulated by the rotation rate or day length. This was due to the strong modulation of the atmospheric heat transport. However, the local-scale phenomena that result from these planetary-scale changes are diverse and sometimes unexpected. This highlights that the system at the center of the course, 'Physics of Climate', is complex, nonlinear, and that its dynamics, when it is taken far from its present-day conditions, are not well understood.

In summary, including activating elements in teaching the physics of climate is challenging, time-consuming, and rewarding. It requires having to constantly balance guidance and flexibility. The challenge of the technical setup cannot be overestimated. When state-of-the-art methods are introduced, teaching assistants and dedicated time for course development are required to ensure success.

Acknowledgements

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Appendix

Excerpt from the Module Handbook

The course 'Physics of Climate' is described in UNIVERSITY HEIDELBERG (2018). The following is an excerpt from this module handbook.

Objectives: Students achieve an advanced understanding of the climate system and the methods to study it, including its changes in the past and the modern human impact on it. They are able to solve advanced problems and interpret the results in the context of current research questions and societal implications. They can competently and critically assess the public discourse on climate change on the basis of the current scientific literature. They have developed a knowledge base that enables them to conduct independent master research projects in physics of climate.

Contents:

- The sun and its variability (orbital and solar physics)
- Ocean and atmosphere and their recent changes
- Cryosphere and water cycle
- Isotope tools
- Radiative transfer and climate
- Climate stability and run-away climate variability
- The carbon cycle
- Climate sensitivity, heat capacity, response times
- Prediction of climate change

- **Workload:** 120h, 4CP, English, Lecture (2hrs/week), Exercise with homework (1hr/week); Examination: written exam.

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Table 2: Timeline of the Physics of Climate class in summer term 2020. Lecturers: Samuel Hammer (SH), Klaus Pfeilsticker (KP), Kira Rehfeld (KR). Student actions include learning goals through the weekly assignment. P0-P8: project-related assignments.

Week	Date	Topic	Lecturer	Teaching tools/formats	Learning goal	Student actions
1	2020-04-22	**Introduction, climate system**	SH	Lecture (+Mentimeter), 90min	explain climate system	Read + answer questions about 1.5degree report;
2	2020-04-27	**Atmosphere-Ocean heat engine**	KR	synchronous lecture, 90min	describe planetary thermodynamics and the role of water in the atmosphere	Calculate heat-to-work transformation in thunderstorm;
3	2020-05-06	**Wave-driven transport I**	KP	synchronous lecture, 90min	outline global atmospheric dynamics	Deduce Crocco's and Kelvin's theorem;
4	2020-05-13	**Wave-driven transport II**	KP	synchronous lecture, 90min	derive atmospheric vorticity	Explain jet stream and Rossby waves;
5	2020-05-20	**Scientific method, climate statistics**	KR	Climate Explorer (Video-Snippet, 5min)+ synchronous lecture+exercise with breakout/padlet, (60min) + Statistics/Model (Video-lecture, 30min)	use simple statistics to quantify climate dynamics	Implementation 0D-EBM, time series analysis (1D data);
6	2020-05-27	**Nonlinear models**	KR	Question-Answer-Forum (no synchronous lecture due to power outage/fire alarm)	implement and visualize a nonlinear system of equations in 3D	Visualization of energy balance variables from netcdf files (2D data);
7	2020-06-03	**Tipping points and PLASIM how-to**	KR	synchronous lecture, 60min + setup video (20min)	describe tipping points and install climate model	P0: Setup of PLASIM OR describe PLASIM;
8	2020-06-10	**Projects and the Planet Simulator**	KR	Synchronous lecture, Cryptpad (Groups/Experiments/Control results)	explain planetary vorticity and design model experiments to evaluate climate impacts	P1: Choose and motivate a project investigating climate feature in class experiment (scale 1-3), outline analytic plan, and request necessary climate variables;
9	2020-06-17	**Impact of planetary vorticity change**	KR	Discussion and 3 breakout rooms according to climate variables (3D, daily, 2D/monthly) → Forum entry for each set of groups to post experiment plans, questions	formulate hypothesis and outline feasible analysis workflow to test it	P2: Run experiments OR find and review 1 paper on the chosen climate feature; submit slide with sketch of analysis/key figure.
10	2020-06-24	**Ocean carbon cycle**	SH	Synchronous lecture + discussion of analysis sketches (tutorium)	describe ocean carbon cycle	P3: Validate and analyze data, detail further plans; submit slide with first results.
11	2020-07-01	**Terrestrial carbon cycle**	SH	Synchronous lecture+ written instructions for Handout/Video/Presentation (Overleaf/OnlyOffice/Jabref/OBS)	describe terrestrial carbon fluxes	P4: Draft handout (max. 5p)
12	2020-07-08	**Radiocarbon**	SH	Synchronous lecture, forum	describe use of radiocarbon	P5: Peer review; carbon cycle problem
13	2020-07-15	**Methane cycle**	SH	Synchronous lecture Peer review forum	describe methane cycle	P6: peer review implementation (forum); carbon cycle problem
14	2020-07-22	**Climate variability**	KR	Synchronous lecture/discussion, peer review corrections;	distinguish time/space scales of weather and climate	P7: Revision of handout, presentation and video;
15	2020-07-29	**Results: planetary vorticity change**	KR	synchronous lecture/discussion, video forum	describe connections between global and local climate changes	P8: Discussion and reflection