NICOLE AESCHBACH, DAVID RÖCK, KATHRIN FOSHAG, EDITH ENGELHARDT, LOUISA MOSMANN AND WERNER AESCHBACH

Climate Physics meets *Education for Sustainable Development*

How to address *wicked problems* through *blended learning*

ABSTRACT

Many of the current societal challenges, such as the climate crisis, are so-called *wicked problems*, i.e., they are characterised by a high degree of complexity and a multitude of conflicting goals. Innovative learning settings are needed to address these issues in a research and skills-oriented way. The module *Climate Physics meets ESD* was designed for future teachers of *STEM* (science, technology, engineering, and maths) subjects. It consists of online and face-to-face elements that closely interweave the acquisition of competences in the field of *Education for Sustainable Development (ESD)* with learning activities on climate physics. The start-up phase of the new course was funded by the Stifterverband and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg as part of the programme "Fellowships for Teaching Innovations and Support Services in Digital University Teaching". The project is hosted by the Heidelberg School of Education (HSE), a joint institution of Heidelberg University and Heidelberg University of Education, in collaboration with the Faculty of Physics and Astronomy of Heidelberg University.

The article provides an insight into the design and testing phase, as well as the theory- and reflection-based revision. The initial three-part structure of the module was further developed into a *blended learning* approach with more frequent alternation between online and classroom learning. The potential of digital and research-oriented settings in university teaching is demonstrated in the light of the social transformation processes of our time.

Keywords: Climate physics – Climate change – Education for Sustainable Development – STEM – Blended learning

ZUSAMMENFASSUNG

Viele der aktuellen gesellschaftlichen Herausforderungen, wie die Klimakrise, sind so genannte *wicked problems*, das heißt sie sind von einem hohen Maß an Komplexität sowie einer Vielzahl von Zielkonflikten geprägt. Um diese anspruchsvollen Themenfelder forschungs- und kompetenzorientiert in der Lehre zu adressieren, sind innovative Settings erforderlich. Das Modul *Klimaphysik meets BNE* für Lehramtsstudierende der *MINT*-Fächer (Mathematik, Informatik, Naturwissenschaften und Technik) besteht aus Online- und Präsenzelementen, die den Kompetenzerwerb im Bereich *Bildung für Nachhaltige Entwicklung (BNE)* mit Lehr-Lernaktivitäten zur Klimaphysik eng verschränken. Die Aufbauphase des neuen Lehrangebots an der Heidelberg School of Education (HSE), einer gemeinsamen Einrichtung von Universität Heidelberg und Pädagogischer Hochschule Heidelberg sowie

an der Fakultät für Physik und Astronomie der Universität Heidelberg wurde vom Stifterverband und vom Ministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg im Rahmen des Programms „Fellowships für Lehrinnovationen und Unterstützungsangebote in der digitalen Hochschullehre“ gefördert.
Der Artikel gibt einen Einblick in die Konzeptions- und Erprobungsphase sowie in die theorie- und reflexionsbasierte Weiterentwicklung des zunächst dreiteiligen Aufbaus des Moduls zu einem *Blended-Learning*-Ansatz mit häufigeren Wechseln zwischen Online- und Präsenzlernen. Es wird aufgezeigt, welches Potential digitale und forschungsorientierte Settings in der Hochschullehre mit Blick auf die anstehenden gesellschaftlichen Transformationsprozesse haben.

Schlagworte: Klimaphysik – Klimawandel – Bildung für nachhaltige Entwicklung – MINT – Blended Learning

Initial Situation

Learning and teaching in times of multiple crises

The climate crisis is a major challenge of our time, but it is by no means the only one. In order to find effective solutions and to enable as many people as possible to participate in the transformations that lie ahead, learning and teaching must also change. “We are increasingly asking if what people learn is truly relevant to their lives, if what they learn helps to ensure the survival of our planet. *Education for Sustainable Development (ESD)* can provide the knowledge, awareness and action that empower people to transform themselves and transform societies”, states Stefania Giannini, Assistant-Director-General for Education at the United Nations Educational Scientific and Cultural Organization (UNESCO 2020: 3). In view of the multiple crises of our time, the so-called *Learning compass 2030*, published by the Organisation for Economic Cooperation and Development, points out: “Students need support in developing not only knowledge and skills but also attitudes and values, which can guide them towards ethical and responsible actions. At the same time, they need opportunities to develop their creative ingenuity to help propel humanity towards a bright future.” (OECD 2019: 5).

Tackling the climate crisis as a complex and so-called *wicked problem* (see KNUTTI 2019) has been one of the most pressing challenges at all levels for decades. *Wicked problems* are characterised by a high degree of complexity, of interdependency between sub-aspects, and of difficulty in finding solutions, particularly because of conflicting objectives. In order to address the topic of the climate crisis in education adequately, it is necessary to make sound knowledge from research available and applicable in terms of sustainable development and to exploit the possibilities of digitalisation profitably. The natural sciences as well as the humanities and social sciences can provide the basic knowledge on the causes, impacts and mitigation of human-induced climate change. In the development of competences for action, the embedding of specialised knowledge in overarching concepts of sustainable development plays an important role. Teaching and learning in higher education can make a significant contribution to achieving Goal 4 of the United Nations' *Sustainable Development Goals (SDGs)*: "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" (UN 2015: 14). Since 2016, the guiding perspective *Education for Sustainable Development (ESD)* has been anchored in the curricula of general education schools in the German state of Baden-Württemberg, with the aim of implementing *ESD* in all subjects (MINISTERIUM FÜR KULTUS, JUGEND UND SPORT BADEN-WÜRTTEMBERG 2016; AESCHBACH 2022). The use of digital media, tools and learning environments offers many opportunities, but also challenges. An innovative teaching-learning programme on a *wicked problem* such as the climate crisis will benefit greatly from the use of freely available research data, from the possibilities of digital collaboration, and from the mix of synchronous and asynchronous as well as analogue and virtual formats.

This article presents the conception and further development of the module *Climate Physics meets ESD*. Starting from the identified gaps in the study programmes, the learning objectives and the elements of the course are elucidated. Based on the reflection of the pilot run of the course, a contextualisation in *blended learning* approaches as well as a look behind the scenes of the revision of the module is given. The authors see and justify the great potential of innovative teaching-learning settings as a contribution to the transformations in face of the multiple *wicked problems* of our time.

Challenges and opportunities identified

Considering the challenge of addressing *wicked problems* with innovative teaching formats, Nicole Aeschbach and Werner Aeschbach launched the proposal *Climate Physics meets ESD*. Their project received funding from the Stifterverband and the Ministry of Science, Research and the Arts of the State of Baden-Württemberg (STIFTERVERBAND 2023) for the conception and testing phase. Thematically, conceptually and structurally, the project aims to close several gaps as follows: (1) The innovations in digital teaching designed during the COVID-19 semesters will be used and further developed in an exemplary way on a current interdisciplinary topic in two institutions. (2) The module will enhance the visibility of digital teaching as an example of good practice and will become an inspiration for lecturers of other subjects using the HSE Digital Teaching and Learning Lab (HEIDELBERG SCHOOL OF EDUCATION b). (3) The HSE *Additional/Cross-curricular Qualification Sustainability* will build the bridge from *ESD* to physics that is missing so far. (4) The module will provide the Physics Department with an initial impetus to develop a course on climate physics specifically for future teachers. (5) The integration of *ESD* as a guiding perspective in university teaching will be promoted. (6) The scientifically and socially relevant topic of climate change will be innovatively addressed using digital resources, such as online climate data. (7) Students acquire scientific and *ESD* competences and work in a mix of self-learning and interaction phases.

With the *Additional/Cross-curricular Qualification Sustainability* launched in spring 2022, the Heidelberg School of Education (HSE) offers a programme for future teachers of all subjects at Heidelberg University and University of Education Heidelberg. While the courses use both face-to-face and asynchronous online formats to ensure compatibility with the participants' curricular schedules, there is further potential to enhance the digital settings successfully practised during the COVID-19 pandemic. The literature discusses the emerging opportunities and tensions in digital university teaching in a variety of ways. Domes and Spindler (2022), for example, summarise the potential based on current studies as follows: "(a) making learning more flexible in terms of place and time; (b) expanding opportunities in terms of communication, networking, cooperation, and collaboration; (c) enabling different approaches to learning content and increasing self-determination in the learning process" (DOMES & SPINDLER 2022: 123). Especially in the combination of digital-only and digitally enhanced classroom settings, there is still further potential for innovation. Often, the implementation is challenging because the rooms are not adequately equipped. The HSE Digital Teaching and Learning Lab (P18) offers excellent conditions: flexible furnishings, room dividers, touch screens, iPads, and a makerspace with high-quality equipment for creating audio and video products enable flexible analogue and digital teaching and learning. To encourage lecturers from as many disciplines as possible, teaching-learning activities need to be designed and implemented in P18 to serve as showcases and inspiration.

Another challenge is the need for research-oriented digital and *blended learning* courses for future teachers at the interface of *ESD* and *STEM* (science, technology, engineering, and maths) subjects. The guiding perspective of *ESD* has so far hardly been anchored at universities (cf. the current "National Monitoring Education for Sustainable Development" published by HOLST & SINGER-BRODOWSKI 2022). The modules offered in the HSE *Additional/Cross-curricular Qualification Sustainability* have not yet included courses specifically targeted to *STEM* students.

The Faculty of Physics and Astronomy at Heidelberg University has identified the following gap: in the highly topical and scientifically and socially relevant subject area of climate change, there is no course on offer specifically for future physics teachers. The existing *Environmental Physics* undergraduate course is too extensive and demanding for students aiming to become physics teachers to integrate it into their regular curriculum. The new *Climate Physics meets ESD* course, by contrast, provides students of *STEM* subjects with a solid, physics-based grounding in climate science and thus contributes to the dissemination of these skills, which are essential for the future viability of society. Specifically for physics students, it fills an existing gap and provides material that can later be integrated into the curriculum of physics for future teachers. The digital elements are seen as an advantage, as they should facilitate the integration of the course into the already very busy curricula of teacher students.

The number of students in the bachelor's programme with Teaching Degree Option and the Master of Education (M.Ed.) programme in Physics is small (in the winter semester 2022/23, a total of 73 students were enrolled in the B.Sc. programme in Physics with Teaching Degree Option and 20 students in the M.Ed. programme in Physics), while at the same time there is a high demand from schools and very good recruitment opportunities (MINISTERIUM FÜR KULTUS, JUGEND UND SPORT BADEN-WÜRTTEMBERG 2022). The topic of climate change is well suited to introduce and illustrate many concepts of physics in the context of a current issue of high relevance. Therefore, the implementation of a climate physics module has the potential to contribute to the attractiveness of both physics teacher training and physics education in schools.

Perspectives from *ESD*, environmental physics, and digitalisation

To design a teaching programme successfully at the intersection of climate physics, *ESD*, and digitalisation, multiple perspectives must be closely integrated. The project funding *Fellowships for Teaching Innovations and Support Services in Digital Higher Education* of the Stifterverband and the Ministry of Science, Research and the Arts Baden-Württemberg explicitly aims at the formation of a teaching tandem. The geographer Nicole Aeschbach and the physicist Werner Aeschbach form such a tandem in the project *Climate Physics meets ESD*, which was successful in this call for proposals.

Building on her professional background in geography with a focus on transdisciplinary research on climate change mitigation and adaptation, Nicole Aeschbach has been involved in teaching at the Department of Geography at Heidelberg University for more than ten years. During her time as managing director of the Heidelberg Center for the Environment (HCE), she has positioned herself more and more in an interdisciplinary way and has been intensively involved in *ESD* research and teaching. Inspired by further training courses in university didactics with the Department for Teaching and Learning at the heiSKILLS centre at Heidelberg University, her teaching has increasingly focused on innovative, activating teaching-learning settings. Nicole Aeschbach experienced a personal digital innovation boost in the spring and summer of 2020 when transferring her seminar *ClimateChangeKnowledge* to the online format. Nominated by the students and selected by the Rectorate of Heidelberg University, she was awarded a prize for digital teaching (HEIDELBERG UNIVERSITY 2020) at the end of 2020. Nicole Aeschbach has reflected upon the seminar in a previous article in the journal HINT (AESCHBACH 2021). She used the prize money from the teaching award to set up the *ClimateChangeKnowledge StudentLab*, an online exhibition designed by students (TDLAB GEOGRAPHY). Since fall 2021, Nicole Aeschbach has been active in teaching development at the HSE, where she is establishing the *Additional/Cross-curricular Qualification*

Sustainability (HEIDELBERG SCHOOL OF EDUCATION a.). Digital elements play a major role here as well.

Werner Aeschbach also attaches great importance to communicating the results of climate research to a wide range of target groups both within and outside the scientific community, and especially to students of *STEM* subjects and to (future) teachers. He regularly contributes to climate change education as a lecturer in the undergraduate course *Environmental Physics*, which is very popular with physics bachelor's and master's students (currently around 100 participants per semester). At the beginning of the COVID-19 pandemic, this course was converted to an online format at short notice. Together with his co-lecturer André Butz, Werner Aeschbach received the teaching award of the Faculty of Physics and Astronomy for the summer semester 2020. The concept of lecture videos and question and answer sessions in the *inverted classroom* modus – i. e. the concept of asynchronous lecture videos followed by synchronous question and answer sessions – was very well received by the students. This success motivates Werner Aeschbach to continue using the advantages of digital teaching formats and to further optimise them in his teaching.

With the help of the funding, it was possible to put together a teaching team that, in addition to the two fellows, includes Kathrin Foshag and Edith Engelhardt, one postdoctoral researcher each from the *ESD* and physics fields. Additionally, the team saw the need to integrate further *STEM* subjects as well as student perspectives especially in the iterative elaboration and testing loops. The group was thus fortunate to include several students in the project: Tanja Griesbaum (M.Ed. candidate in English Studies and Geography), Julian Haas (M.Ed. candidate in Chemistry and Geography), Emmy Hieronimus (M.Sc. candidate in Physics), Berit Lindemann (M.Ed. candidate in German Studies and Geography), Louisa Mosmann (M.Ed. candidate in Biology and Geography), and Alexander Werner (M.Ed. candidate in Mathematics and Physics). Their intensive participation in the conception of the content and digital design of the self-learning elements is of immense importance to the entire development of the module. Attending the first round of the course as a participant, David Röck (M.Ed. candidate in Geography and Economics as well as in History, Social Studies and Political Education at the University of Innsbruck, Austria) takes an active position in the team in the further development of the course presented later in this article. Christoph Bertolo, a media expert at HSE, plays an equally important role. He is responsible for the production of the learning videos and for running a media workshop with the participants in the HSE Digital Teaching and Learning Lab.

Objectives

The aim of the module *Climate Physics meets ESD* is to combine the current state of the art in physics on climate change with teaching-learning approaches from *ESD*, thereby creating an innovative *blended learning* course for future teachers of *STEM* subjects. In order to develop the triad *research-oriented – digital –practice-oriented* in a well-founded way, the expertise from geography, transdisciplinary climate and sustainability research, environmental physics, teaching development and teacher training is needed.

The module has the following learning objectives:

Students completing the module will
- be able to describe the basics of the concepts of sustainability and *ESD*,
- make a connection between the guiding perspective of *ESD* and their own *STEM* subject,
- be able to explain the physical principles of the climate system and climate change,
- be able to independently research and analyse current data on the causes and impacts of climate change with the help of digital sources and tools, and apply them to concrete questions in the sense of research-oriented learning (cf. i. a. HEALY & JENKINS 2009),
- be able to describe important processes in the climate system quantitatively and qualitatively using knowledge of physical processes, and to explain relationships between individual processes and subsystems,
- have a basis of scientific understanding enabling them to assess the effectiveness of measures of climate action and adaptation to the impacts of climate change,
- have familiarised themselves with the possibilities of the HSE Digital Teaching and Learning Lab and be ready to independently use the media equipment to produce digital learning materials, and
- have created digital learning materials with a climate physics context for use in their own *STEM* subject.

The topic area of climate change is very well suited for combining scientific, societal, and practical aspects in teacher education. Although there is a wide range of climate change education offerings for different target groups, they do not combine the scientific depth of physics with *ESD* perspectives and are not explicitly aimed at teacher training at universities.

Presentation and reflection of the learning phases

The module was planned in a three-phase structure (see Figure 1) and implemented for the first time in the summer semester 2023. Ten students enrolled in this pilot run. Five students attended the module as part of the HSE *Additional/Cross-curricular Qualification Sustainability*; the *STEM* subjects represented were geography, mathematics, biology and chemistry. Four participants came from physics, and one Erasmus student from geography chose to take the course as an additional activity.

The aim of the three-phase structure was to combine the advantages of the self-learning phase (receptive phase 1), which can be completed flexibly in terms of time, and the self-directed learning phase for the creation of digital teaching materials (productive phase 3) with a professionally and socially intensive classroom phase (interactive phase 2).

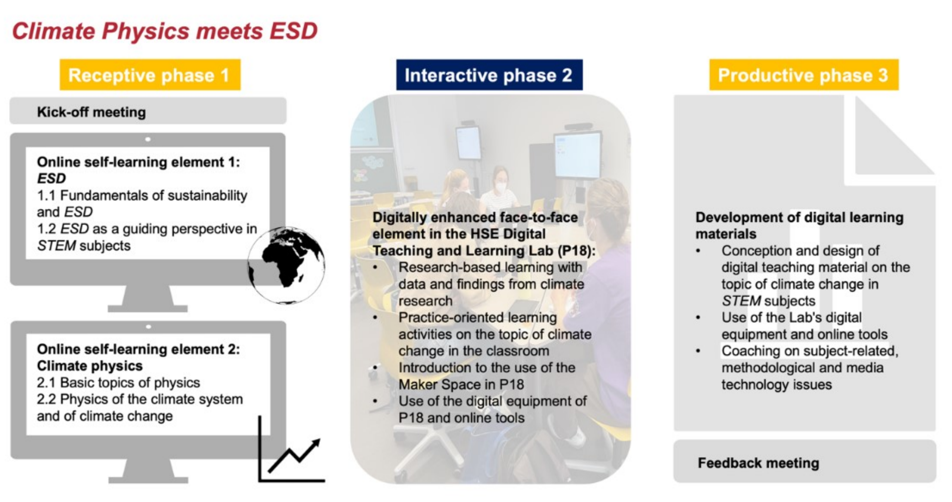

Figure 1
Structure of the *Climate Physics meets ESD* module as designed for the pilot phase. The module combines self-learning and classroom activities in three phases.

Self-learning elements in phase 1

The first phase was designed to provide basic skills in *ESD* and climate physics. After a synchronous online kick-off meeting, participants acquired knowledge about sustainability, the guiding perspective of *ESD* and the physics of the climate system and climate change through online self-learning elements (SLEs). The two propaedeutic elements 1.1 and 2.1 introduce the terms and concepts of *ESD* and selected basics from physics (e.g., radiation laws and elementary thermodynamics for non-physicists) respectively, which are a prerequisite for understanding the following units. Element 1.2 introduces the idea of the guiding perspective of *ESD* from the Baden-Württemberg curriculum. Element 2.2 familiarises students with basic knowledge of physics of the climate system and climate change (e.g., global radiation balance and greenhouse effect). Depending on the field of study, the students completed all four elements or a selection thereof to supplement their previous knowledge. During this initial period of self-study, students could book coaching offered by the teaching team, particularly for the physics sections.

Self-learning element 1.1 on fundamentals of sustainability

In order to embed the issue of the climate crisis in the context of the so-called *grand challenges* (WISSENSCHAFTSRAT 2015), the learners need to be familiarised with some of the basic concepts related to sustainability. In SLE 1.1, learning videos newly produced for the module, introduce the following concepts:

- *Earth Overshoot Day* (GLOBAL FOOTPRINT NETWORK a.)
- *Anthropocene* (CRUTZEN 2002)
- *Planetary Boundaries* (ROCKSTRÖM ET AL. 2009)
- *Ecological* and *Carbon Footprint* (GLOBAL FOOTPRINT NETWORK b.)
- *Doughnut Economics* (RAWORTH 2017)
- *Agenda 2030* with the *Sustainable Development Goals (SDGs)* (UN 2015)
- Paris Agreement (UNITED NATIONS FRAMEWORK CONVENTION IN CLIMATE CHANGE UNFCCC 2015).

These videos provide a brief insight into transdisciplinary research approaches (e.g. LANG ET AL. 2012). The learning videos are accompanied by interactive exercises, the arrangement of which is shown in Table 1. The videos and tasks are provided as H5P sections. H5P is a free software for designing digital learning content. The H5P elements are embedded in a Moodle course, which also provides the exercise sheets, further material, and organisational information about the course.

Mankind and the environment out of balance
— Video introducing the concepts of the Earth Overshoot Day, the Anthropocene, the Planetary Boundaries, the Ecological and Carbon Footprint, and the Grand Challenges
— Quiz
— Exercise: Ranking the effectiveness of individual climate action measures
— Exercise: Calculation of the individual Carbon Footprint followed by the reflection of the results and inspirations for everyday life
A good life for all – here and now, globally and in the future
— Video introducing the concepts of the Doughnut Economy, sustainability, the Agenda 2030, the Paris Agreement, climate change mitigation and adaptation, and transdisciplinarity
— Quiz

Table 1
Content outline for self-learning element 1.1 *Fundamentals of sustainability.*

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Self-learning element 1.2 on the guiding perspective of ESD in the teaching of STEM subjects

Self-learning element 1.2 focuses on *ESD* as one of the guiding perspectives in *STEM* education and includes the basics covered in self-learning element 1.1. The aim of dealing with the *ESD* perspective is to become aware of the links between *ESD* and the different *STEM* subjects and to establish these links directly in the different teaching levels. The curricula are freely available online for all types of general education schools (MINISTERIUM FÜR KULTUS, JUGEND UND SPORT BADEN-WÜRTTEMBERG 2016 a.). The embedding of the guiding perspective in the Baden-Württemberg curriculum for all school types is achieved through the following elements (MINISTERIUM FÜR KULTUS, JUGEND UND SPORT BADEN-WÜRTTEMBERG 2016 b.):

- Relevance of and threats to sustainable development
- Complexity and dynamics of sustainable development
- Values and norms in decision-making
- Criteria for actions that promote and hinder sustainability
- Participation, cooperation, co-determination
- Capacity for democracy
- Strategies for peace

The participants learn how to use the curricula of their subject independently to get information for lesson preparation and get to know the specific reference structure of the online curricula. A matrix called *ESD in my STEM subject* is provided to discuss the curricula of the different *STEM* subjects in depth. The matrix guides the participants through the elements of the curricula and encourages them to reflect on the following aspects: guiding ideas for the acquisition of competences, process-related competences, standards for content-related competences and operators included in the curricula, to examine the role of *ESD* in their subject and to derive concrete, practical references to relevant issues. In addition to identifying the co-benefits of actively integrating the *ESD* perspective, reflecting on possible challenges in everyday teaching is also a central element of the matrix-supported evaluation of the curricula. In a further step, the study of *ESD*-related competences, e.g., based on Gerhard de Haan's concept (*Gestaltungskompetenz,* see e.g., DE HAAN 2008) and the *Rounder Sense of Purpose* (VARE ET AL. 2019) should also help participants to develop cross-curricular and interdisciplinary links to other subjects and relevant topics. The contents mentioned, through which the participants are guided by the matrix, are summarised in Table 2.

Getting to know the *STEM* curricula
— Exploring the online version, including the reference structure
— Examination of the different elements of the curriculum of one's own subject(s)
— Getting to know and distinguishing between competences and key perspectives
Video introducing the content of *ESD*
Pedagogical framework for teaching and implementing sustainability in an educational context
— *ESD*-related competences (*Gestaltungskompetenz)*
— Rounder sense of purpose
Embedding *ESD* in the curriculum
— Guiding perspective on *ESD* in one's own *STEM* subject(s)
— Examining and evaluating the role of *ESD* in one's own subject(s)

Table 2
Content outline for self-learning element 1.2 *ESD as a guiding perspective in teaching STEM subjects.*

During the first face-to-face workshop that followed the self-study phase, participants emphasised the importance of linking subject content, the *ESD* perspective and practical information on how to deal with relevant issues. This contextualisation is often neglected during the first phase of teacher education but plays a central role in everyday teaching.

Self-learning element 2.1 on relevant basic topics of physics
Self-learning element 2.1 serves to provide the basic physical and mathematical knowledge required to effectively follow and understand the physical concepts presented in self-learning element 2.2 (climate physics). This element specifically targets students of *STEM*-subjects other than physics and aims to provide a quantitative (mathematical) understanding as well as qualitative (conceptual) knowledge of basic physical principles. All relevant fundamental physical quantities for element 2.2 are introduced, and the mathematical equations describing and relating them to one another are presented. The self-learning element is structured into three lessons: (1) classical mechanics, (2) thermodynamics, and (3) fluid mechanics (see Table 3). The lessons contain practice-oriented exercises regarding energy conversion and efficiency, e.g. the power of hydro energy and the efficiency of electric and combustion engines in vehicles.

(1) Mechanics: This lesson introduces basic equations of motion together with the relevant physical quantities (velocity, acceleration, force, and momentum) to serve as a base for all following concepts. Furthermore, the very important notions of energy and its conservation are introduced as a prerequisite to understand the concepts of energy balance and energy transformation in the climate system discussed in element 2.2.

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(2) Thermodynamics: In this lesson, important thermodynamic state variables (such as temperature and pressure) and properties (such as latent heat and heat capacity) are introduced. A particular focus lies on basic concepts of the transformation of thermal energy, including conversion efficiency, and on heat transport, including thermal radiation. Thus, it provides the essential physical knowledge to understand topics such as the Earth's radiation budget, the role of greenhouse gases in the climate system, and the concept of radiative forcing discussed in element 2.2.
(3) Fluid mechanics: This lesson explains basic physical principles of hydrostatics and fluid dynamics to equip students with a basic qualitative knowledge about fluid mechanics, in order to understand the motion of fluids (e.g., ocean water and atmospheric air) and the corresponding transport processes in the climate system.

Lesson 1: Mechanics
— Velocity and acceleration
— Force, Newton's axioms
— Energy, different forms, conservation, and transformation
— Momentum and its conservation
— Pressure, hydrostatic pressure profiles in air and water
— Waves, frequency, and wavelength
Lesson 2: Thermodynamics
— Temperature, microscopic interpretation
— Thermodynamic state variables, ideal gas law
— Heat capacity and latent heat
— Transformation of thermal energy, conversion efficiency
— Heat transport (conduction, convection, and thermal radiation)
Lesson 3: Fluid mechanics
— Hydrostatic pressure and buoyancy
— Viscosity, laminar and turbulent flow
— Fluid dynamics: continuity
— Fluid mechanics in everyday phenomena

Table 3
Content outline for self-study element 2.1 *Preparatory course on physics fundamentals*

Self-learning element 2.2 on climate physics

The fundamental idea and goal of self-learning element 2.2 (climate physics) is to convey a concrete, quantitative and process-based understanding of climate change to the students. Even though most students are highly aware of the climate change problem and its general cause, they often are not able to explain adequately how greenhouse gases cause global warming or to classify the impact of different greenhouse gas emissions or mitigation measures in a quantitative way. Given that the transformation towards a climate-neutral world adhering to the Paris climate targets is an increasingly important theme in society and economy, it is of high importance that future teachers are familiar with the fundamental concepts behind these goals. Moreover, the new course is designed to enable them to update their climate change knowledge as the science as well as the state of the climate system and the anthropogenic impact on it are continuously evolving.

The main learning objective of this element is that students develop a thorough understanding of fundamental concepts of climate science. They thus are able to evaluate quantitative relationships between greenhouse gas emissions, resulting changes in the atmosphere and hence the global radiation balance, and ultimately their impact on global temperatures and other aspects of the climate system. These concepts and relations are physical in nature but are accessible also for students from *STEM* subjects other than physics. However, they are usually not even part of the curriculum in physics, which makes this course a rare opportunity for future *STEM* teachers to obtain an in-depth grasp of climate change science. In order to support learners in acquiring competences and to be able to measure learning success, the climate physics lessons contain learning materials (specially created learning videos as well as information texts and graphics) and tasks. The tasks are, on the one hand, integrated in the H5P elements in the form of quizzes and, on the other hand, are designed as classical exercise sheets. Students work on the problems and submit the results via Moodle. The lecturers comment on the submissions and provide feedback to the learners.

While the climate physics element covers all relevant aspects of the climate system (see Table 4), it focuses particularly on the quantitative links between the different changes in the climate system. A central tool is a strongly simplified but conceptually highly useful energy balance model of Earth, as presented e.g. in the textbook of Hartmann (2016). This model enables the students to understand the concept of radiative forcing as a driver of climate change. The same model is also used to introduce the positive and negative feedbacks in the climate system, which are of pivotal importance to estimate climate sensitivity. The relatively complex issue of feedbacks makes this central climate science parameter hard to quantify, which is a major source of uncertainty of climate projections. On the other hand, given the climate sensitivity, the calculation of the expected equilibrium warming is straightforward and comprehensible for students. Based on this physical knowledge it becomes clear that the warming currently observed and expected for the future is directly linked to the global radiation imbalance of the Earth caused by greenhouse gases, which needs to be eliminated in order to stop further warming. By discussing the concept of a limited budget of future emissions, students can assess the feasibility of achieving climate policy goals to limit global warming (ROGELJ ET AL. 2019).

Lesson 1: Introduction and compartments of the climate system
— History of climate science
— The climate system and its spheres
Lesson 2: Global radiation balance and the greenhouse effect
— Radiation laws, solar irradiation on Earth and thermal emission
— Global energy balance model, emission temperature, greenhouse effect
— Imbalance of the current global energy budget
Lesson 3: Earth's fluid systems and their dynamics
— Properties and structure of atmosphere and ocean
— Energy transport and storage in atmosphere and ocean
— Brief introduction to the dynamics of atmosphere and ocean
Lesson 4: System analysis and modelling
— Model concepts for environmental systems, linear box models
Lesson 5: Carbon cycle
— Modern change of atmospheric carbon dioxide and its causes
— Box models of the carbon cycle, sources and sinks, history of emissions
Lesson 6: Radiative forcing and global warming
— Radiative forcing by CO_2 and other causes
— Climate sensitivity and feedbacks in the climate system
— Temperature response of the Earth to radiative forcing in energy balance model
Lesson 7: Climate data and climate models
— Natural climate variability and paleoclimate
— Climate models: Principles and historic development
— Attribution of weather extremes to anthropogenic climate change
Lesson 8: Climate change, climate projections, and climate action
— The current state of climate, observed warming and its impacts
— Climate projections for future emission scenarios
— Climate mitigation targets, emission budget and pathways
— Decarbonisation, transformation to climate neutrality, challenges and benefits

Table 4
Content outline for self-learning element 2.2 *Climate physics*

Face-to-face elements in phase 2

In the second phase, a three-day block seminar took place in the HSE Digital Teaching and Learning Lab (P18). Assessments in the form of quizzes were carried out in plenary sessions for SLE 1 and SLE 2 in order to evaluate the learning progress of the participants after the self-learning phase. Working together in plenary and in groups, the participants had the opportunity to reflect on the first phase, to link their own *STEM* subjects with the guiding perspective of *ESD*. Furthermore, the students were able to embed the knowledge gained from climate physics in the current social discourse on the climate crisis: At different learning stations, the participants received impulses on data sources from climate research, on methods suitable for *ESD*-oriented teaching and on the outlook for phase 3. Participants developed topics for their digital teaching materials and learned in a workshop with media expert Christoph Bertolo how to create video clips and animated graphics using tablets and smartphones. In this way, technical and methodological impulses were combined with interactive group phases. Dealing with current climate data supports the development of climate data literacy. The interdisciplinary composition of the project team creates space for critical and reflective discussions on relevant aspects of the climate crisis. The conceptual approaches from *ESD* (see section on SLE 1.2) broaden the horizons of *STEM* students with regard to adopting perspectives, working together, weighing risks and uncertainties, and dealing with conflicting goals in climate change mitigation.

Phase 2 provided the participants with the benefit of exchanging ideas and discussing their newly obtained knowledge face-to-face both with students of the same subject and with students of other *STEM*-subjects. In that way, the production of first ideas for the digital teaching material was closely interwoven with reflective talks and feedback leading to a productive and reflected draft for the following work phase 3.

Productive Phase 3 and multiplication of the idea

The third phase was dedicated to the participants' independent work on digital teaching materials. The task was as follows: Design a digital teaching material on one aspect of the topic of climate physics with reference to the guiding perspective of *ESD* for use in one of your *STEM* subjects. The material to be submitted consists of the following components: (1) documentation explaining the conceptual embedding of the teaching material in the context of the school curriculum and the guiding perspective on *ESD*, (2) the digital teaching material itself (H5P, audio, video, website or similar). After the materials have been submitted and reviewed by the project team, a feedback meeting will take place. The products were not yet available at the time of writing, so there can be no comment on their quality at this stage.

During a workshop in July 2023, the project team discussed the transferability of the approach to their respective disciplines and institutions with interested *STEM* colleagues

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and teachers. As a joint institution of Heidelberg University and Heidelberg University of Education, HSE is an ideal incubator for further dissemination within the two institutions and in their respective networks.

Reflection and further development

The first run of the *Climate Physics meets ESD* seminar led to a number of considerations for adaptation and revision. At the end of the pilot run, an assessment and evaluation were carried out with the students, which yielded insights that served as a stimulus for the further development of the module. The assessment and evaluation revealed that some of the students had considerable difficulties with the asynchronous processing of the arithmetic problems from climate physics. In addition, the students did not take up the offer of specific coaching on these problems. On the contrary, they reported a high threshold for accepting the coaching format. The coaching offer was designed in such a way that the students had to actively contact the teachers to make an appointment. This format seemed to put the students in an uncomfortable situation that made them reluctant to accept the offer. The assessment of the climate physics SLE showed that the key messages to be conveyed were not sufficiently understood by all students, depending strongly on their prior knowledge and the subjects they were studying.

The face-to-face sessions were designed to deepen the knowledge of climate physics. Unfortunately, this aim could not be adequately achieved as there was not enough time to follow up on students' questions and misconceptions or to contextualise open issues in order to generate further learning progress for them. To develop the seminar further, it is therefore crucial to better link the periods of digital self-learning with the periods of cooperative, interactive learning in the classroom. In this way, students should not be left alone with their difficulties, e.g., when working on the physics calculations, and better learning support should ensure more insight into the students' learning progress. In order to understand how *blended learning* can be implemented profitably for the seminar *Climate Physics meets ESD*, an overview of the empirical conditions for the success of *blended learning* is necessary.

Theoretical inputs for further development

The basic idea of *flipped classroom*, a more specific form of *blended learning*, is to shift the input phases of a unit to asynchronous digital learning phases. In this way, the learners come already prepared to the following face-to-face lessons and with questions about the content. This leaves as much effective interactive learning time as possible for learners and teachers to work together on content-related questions, to complete exercises cooperatively, as well as to discuss and thus deepen knowledge. The teacher's main role is to coach, give feedback and continuously monitor the learner's status to understand developments and assess the need for support. The overall aim of the *flipped classroom* approach is to reduce the amount of talking by the teacher and increase the activity of the students (see WERNER ET AL. 2018).

Kapur et al. (2022) conducted a meta-analysis to investigate the impact of *flipped classroom* learning. In general, they discovered a positive correlation between flipped learning and learning outcomes. However, this relationship does not hold in all situations and seems to depend on a variety of factors. Kapur et al. (2022) found that in many contexts there is little active learning time available in the face-to-face phase. Furthermore, a short theoretical input during the face-to-face phase seems to have a positive effect on learning performance. When there is a lot of active learning time available in the traditional classroom, the positive effect of flipped learning seems to be close to zero. Overall, therefore, it is active learning and not flipped learning per se that is relevant. One advantage of flipped learning is probably the continuous and repeated engagement of the learners with the content.

Several other meta-analyses of *blended learning* came to similar results and show that the use of *blended learning* alone does not have a significant impact on learning performance. Rather, it depends on the organisation of learning in *blended learning*. Both Means et al. (2013) and Wandera (2017) have identified conditions for success in *blended learning* in meta-analyses. Means et al. (2013) found that the use of different learning activities, a maximum of active learning time and interactions between learners were beneficial. According to Wandera's (2017: 91) meta-analysis, eight instructional practices have a significant impact on learning gains: "self-directedness, peer interactions, feedback, multiple learning ways, student orientation, instructor presence, multiple assessments, and accountability". All these empirical findings on the conditions for success of *blended learning* courses have been taken into account in the revised design of the seminar.

Linking reflection and theoretical inputs towards the transformation of a blended learning setting

In order to develop flipped learning while ensuring as much active learning time as possible, Kapur et al. (2022) have developed a four-phase process model consisting of the phases *fail, flip, fix and feed*. This approach has been very inspiring in the development of the *blended learning* concept. In the *fail phase*, learners engage with the new content on their own for the first time, trying out problem-based tasks without assistance. Initial mistakes are not only allowed, but part of the learning process. This was already intended in the original conception of the self-learning phase. After studying the H5P elements and the learning videos, the students worked on physics tasks and submitted them. They then received a corrected and commented version as feedback. This phase should be revised from different points of view: on the one hand, the learners should be given tasks from different levels of educational requirement to work on independently in order to enable internal differentiation. On the other hand, the design of the tasks should include more guidance for students to contextualise the content.

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An additional development of the self-learning phases should be that the students receive more activating problems while working with the learning videos and H5P elements. This should prevent them from only passively consuming the online learning media and lead to actively engaging with them. Werner & Spannagel (2018) identify the active perception of asynchronously used learning videos as a condition for the success of the onboarding phase in the *flipped classroom*. Weidlich & Spannagel (2014) compared the use of learning videos with the use of complex tasks in the phase of learners' initial engagement with the content. Although this was only a small pilot study and the results cannot be generalised due to the small sample size, the results suggest that initial learning with learning videos leads to faster comprehension in the short term, but that learning videos alone do not lead to higher learning gains in the long term. The authors suggest a combined use of learning videos and complex tasks from different requirement levels. This recommendation should be considered in the revised design of the seminar.

After the *fail phase*, the students come to the classroom with their experiences and the knowledge they have acquired in the self-learning phase (see Figure 2). The experiences from the first phase form the starting point for the *flip phase*, in which the understanding of physical climate processes is to be deepened. Kapur et al. (2022) note that making mistakes and being challenged by demanding tasks in the self-learning phase provides additional motivation and a prerequisite for deeper understanding. In this way, students can continue to work on, understand and correct their own misunderstandings and mistakes in class, rather than being confronted directly with ready-made solutions. In the *fix phase*, synchronous teacher input alternates with interactive activities. However, this input is in no way intended to correspond to traditional lecture-style teaching or to repeat the content of the learning videos. The aim is to draw attention to certain key elements, to try to explain with other approaches when things are unclear, and to discuss and deepen content together.

The face-to-face sessions are about addressing learners' difficulties and misunderstandings as well as answering their questions. To achieve this aim, the exercises from the asynchronous self-learning elements should be discussed. In addition, core statements and ambiguities from the self-learning elements such as videos and interactive slides will be reviewed. Further thematic input from the teachers is also possible for wider contextualisation. In the *feed phase*, the students' learning status is assessed, and constructive feedback is given in an attempt to best support the students in their learning process.

At the beginning of the face-to-face sessions in the revised course design, a self-assessment of the basic physics and mathematics is carried out (see Figure 2). This is intended to give the teachers a notion of the students' learning status, which allows for internal differentiation. Based on this self-assessment, two learning groups shall be formed for the climate physics problems that will be solved in the course of the seminar. At the end of the seminar, there will be an assessment of the knowledge and understanding gained by the students (see Figure 2). A comparison of their level before and after the seminar should illuminate the development of their learning and increase in knowledge, thus providing the teachers with feedback on the achievement of the learning objectives.

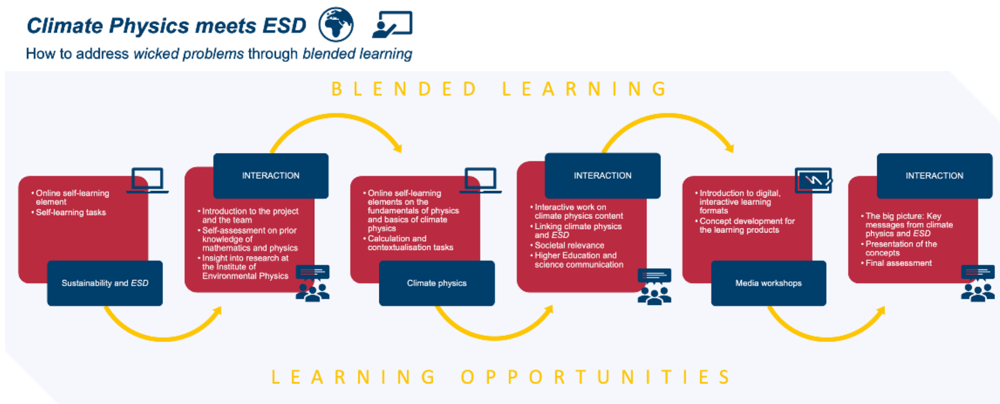

Figure 2
Illustration of the revised structure of the course *Climate Physics meets ESD* with a closer interweaving of the online and classroom elements. The blended learning format, which is consistently implemented, creates a variety of asynchronous and synchronous learning opportunities with the aim of enabling the participants to acquire competences in depth.

In the next run during winter term 2023/24 the seminar will take place at two different locations, the Institute of Environmental Physics and the HSE Digital Teaching and Learning Lab. The Institute of Environmental Physics on the one hand allows giving students insight into research practice, working methods and methods of climate research. This scientific orientation is an important part of the seminar, as it should contribute significantly to an in-depth understanding of climate physics. The facilities of the HSE Digital Teaching and Learning Lab on the other hand are ideal for conducting media workshops with the students, thus providing them with a pool of methods which they can draw on when creating their final learning products. These products should be aimed either at the classroom in the case of the teacher training students, or at the field of science communication and higher education for the other students. Throughout the development of their products, the students will receive feedback from their peers.

The main goal of the in-classroom time and *blended learning* as a whole is that students can characterise the complexities of the climate system and the resulting complexities of climate change. Furthermore, this natural science perspective is to be linked to the social spheres, especially politics, education and science communication, in order to develop a deeper understanding of the *supercomplexity* (see BERGMEISTER, PICHLER & HINTERMANN 2017) around the climate crisis. It is precisely this bringing together of climate physics and aspects of sustainable development that is the core and goal of the seminar.

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Conclusion

The climate crisis is undoubtedly one of the greatest challenges societies are currently facing. To meet science-based and politically agreed limits on global warming, mitigation action is needed in all sectors and at all scales. The climate system itself is characterised by a high degree of complexity and can exhibit non-linear behaviour. However, societal change processes are not necessarily linear either. Otto et al. (2020) have shown in their study "Social tipping dynamics for stabilizing Earth's climate by 2050" that triggering social tipping points in societal systems can bring about profound changes within a short period of time. One field of action addressed in the study is the education system. The study sees "scientists, teachers, educational ministries" (OTTO ET AL. 2020: 2358) as key actors who can effectively change the system. "The presence of climate change and relevant concepts in public education" (OTTO ET AL. 2020: 2358) is the main control parameter. "New educational programs at all levels of public education including climate change, ecological networks, system thinking" (OTTO ET AL. 2020: 2358) are mentioned as examples of interventions. According to the authors, the "critical threshold in the control parameter" is "the relevant concepts becoming a part of the main curriculum." (OTTO ET AL. 2020: 2358)

In this regard, university teaching, which accompanies young people in the acquisition of competences at the interface of research and education, has an immense responsibility. Dealing with the many dimensions of the climate crisis requires learning environments that promote both a deeper understanding of current research and the contextualisation of these findings in social discourse. The *wicked problem* of the climate crisis thus obviously calls for innovative teaching approaches. In the *Climate Physics meets ESD* project, this challenge is met with the help of a *blended learning* approach. The close interweaving of self-learning and exchange in the group as well as with the lecturers creates a basis for substantial competence acquisition. Just as the production of knowledge in research is subject to constant methodological testing, reflection and revision, university teaching should also be flexible and continuously renewed. The *Climate Physics meets ESD* project team therefore sees the four phases of conception, implementation, reflection, and revision towards an improved concept merely as stations on the way to a module that increasingly meets the requirements.

In any case, one of the lessons learned is that high-quality digital elements can significantly improve teaching – but only if they are designed and implemented in a way that is adapted to the learning objectives, the topic and the often heterogeneous target group. In the *Climate Physics meets ESD* project, the experience gained from the pilot run has led to a break-up of the originally planned three-phase structure with a chronological separation of the self-learning and classroom phases to a much more gradual alternation of asynchronous digital learning and on-site sessions.

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Dr. Nicole Aeschbach is a senior scientist at the Heidelberg School of Education (HSE), a joint institution of Heidelberg University and the University of Education Heidelberg. The focus of her work is on the design and implementation of innovative learning settings for future teachers. Nicole Aeschbach is a geographer with a doctorate in paleoclimate research; she founded the TdLab Geography at Heidelberg University. In 2020, she was awarded the Prize for Digital Teaching at Heidelberg University; in 2023, she holds a Fellowship for Digital University Teaching by the Stifterverband and the Ministry of Science, Research and the Arts Baden-Württemberg.

David Röck is a Master of Education student at the University of Innsbruck. He is studying Geography and Economics as well as History, Social Studies and Political Education. He has also taken extra-curricular courses in Philosophy, German Studies and Physics. His Bachelor's thesis in Geography Education dealt with information security in relation to anthropogenic climate change among adolescents and how pupils are prepared for handling misinformation

within geography didactic materials. The Bachelor's thesis in History was on conspiracy theories and fake news. David Röck spent the summer term 2023 as an Erasmus student at Heidelberg University.

Dr. Kathrin Foshag is a researcher and lecturer at the TdLab Geography at the Department of Geography at Heidelberg University. Her research interests include adaptation to the impacts of climate change (in particular the increasing frequency and intensity of heat events in urban areas), transdisciplinary methods for integrating expertise from practice partners, and Education for Sustainable Development. In cooperation with the Heidelberg Center for Education for Sustainable Development at the Heidelberg University of Education, she is leading the Geography module in the Master of Education programme, linking didactics and science in the field of climate change and sustainable development.

Dr. Edith Engelhardt is a researcher in the Hydrospheric Tracers and Proxies Group of Prof. Aeschbach at the Institute of Environmental Physics of Heidelberg University. She is responsible for running the noble gas lab and is involved in the teaching activities of the Faculty of Physics and Astronomy. She graduated with a Master's degree in Physics at Heidelberg University, subsequently did her PhD work at the Swiss Federal Institute of Aquatic Science and Technology (Eawag), and received her doctorate in environmental sciences from ETH Zurich in 2023. Her research focus lies on the analysis of noble gases in aquatic systems.

Louisa Mosmann is a Master of Education student at Heidelberg University studying Geography and Biology. A focus of her studies is on outdoor learning and Education for Sustainable Development (ESD). In that field she is involved in the conception and implementation of courses as a student assistant at the Heidelberg School of Education (HSE). As part of her Master's thesis she designed and implemented a field trip for university students to experience human-environment interactions in the Palatinate Forest and reflect on sustainable behaviours. In 2023 Louisa Mosmann gave a #climatechallenge workshop at a climate communication event.

Prof. Dr. Werner Aeschbach leads the aquatic systems research at the Institute of Environmental Physics of Heidelberg University; his interests encompass physical processes in lakes, oceans and groundwater as well as paleoclimate. He formerly was director of the Heidelberg Center for the Environment (HCE) and currently is speaker of the Heidelberg Graduate School for Physics (HGSFP). He is a physicist with a doctorate in environmental sciences from ETH Zurich. He conducted postdoctoral research at Columbia University, New York. In 2023, he holds a Fellowship for Digital University Teaching by the Stifterverband and the Ministry of Science, Research and the Arts Baden-Württemberg.

Dr. Nicole Aeschbach
aeschbach@heiedu.uni-heidelberg.de