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Teaching climate change in the context of the climate system: A mixed method study on the development of systems thinking skills in German 7th grade students regarding the climate

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Abstract: This paper reports part of a larger study on the development of systems thinking skills in German 7th grade comprehensive school students regarding the climate. Research has shown a fragmented understanding of climate change among students that hardly accounts for the dynamic interrelations in the climate system and may pose a barrier in understanding adaptation and mitigation strategies (Shepardson et al., 2017, 2011, Calmbach 2016). While much is known the impact of short-term interventions on the general system understanding of students, what is lacking to date is 1) a specific intervention on *climate* system understanding and 2) insights into the *process* of developing system understanding in students. Helpful insights in this context come from Conceptual Development theories for they allow the development of systemic thinking to be viewed in terms of conceptual expansion or conceptual change. Starting from these desiderates, a teaching-learning sequence was developed based on the SYSDENE model of system competence (Frischknecht et al. 2008). In the sequence young learners systematically link experiences from formal science education with the experiences at three non-formal learning environments. A mixed-methods approach was used to explore the impact of this 3-month sequence on 19 7th grade students. A written pre-/post-test suggested a significant improvement in Climate System Reconstruction for the group (pre-test Median = 6.75 vs. post-test Median = 12.5, Wilcoxon Test: $p = .003$, $r = .82$). However, a qualitative analysis of classroom conversations, interviews and concept maps indicated that cognitive development toward a higher level of system thinking was neither continuous nor did every student reach it. Moreover, the SYSDENE model's Competence Area "Describe System Model" proves critical. Being able to describe the main climate system factors is not sufficient, one also needs to be able to distinct weather from climate and grasp several scientific concepts related to the climate (e.g. greenhouse effect, water cycle, evaporation, reflection) in order to understand climate as a system.

Keywords: Systems thinking, Climate system, climate change education, non-formal learning, cognitive change

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Introduction

Humans tend to think in linear and descriptive terms (Vollmer, 1986), which makes it particularly challenging to understand problems arising from complex systems such as climate. In fact, the Earth’s climate is a complex, dynamic system whose properties cannot be fully explained by the properties of its system components, and whose dynamics are subject to nonlinear growth laws. The climate system includes several subsystems, namely the sun, the atmosphere, the hydrosphere, the cryosphere, the geosphere, the biosphere, and the anthroposphere. These different subsystems are in physical and chemical exchange with each other, and thus permanently interact and depend on each other. Moreover, climate is a socio-scientific issue, in which scientific, economic, and ecological aspects are strongly intertwined.

Young people reveal a fragmented understanding of climate change that hardly accounts for the mentioned dynamic interrelations in the climate system (Shepardson et al., 2017; Calmbach et al., 2016; Shepardson et al., 2011). As Shepardson et al. put it: “This lack of understanding regarding feedbacks and the inter-relation between climatic components is a significant stumbling block for understanding not only the causes and effects of climate change, but also the adaptive and mitigation strategies that can be devised” (ibid., p.328). Shepardson et al. conclude that climate change should be taught in the context of the climate system.

In the project of which this article is part, a teaching-learning sequence has been developed to tackle this problem. To understand whether this intervention helps students develop an understanding of the complex dynamic processes in the climate system, the development has been empirically guided and assessed. Since not only system understanding is important for this, but also a change in complex ideas, this study includes theories of conceptual development when looking at the learning process.

Literature Review

Empirical studies have documented young people’s reliance on monocausal thinking when searching for solutions to problems or trying to deal with factual complexity (Sweeney and Sterman, 2007; Assaraf & Orion, 2005). This problem is by no means limited to the concept of climate. As early as 2009, Haugwitz and Sandmann (2009) reported: "International school performance studies such as PISA and TIMSS show considerable deficits in [...] interconnected knowledge of German students in the natural sciences" (p. 89). According to the authors, the core of this problem lies in the "complex structure of the natural sciences, which teaching can hardly do justice to" (ibid. p. 89 f.). For instance, German students are said to regularly deal with climate and climate change from the perspective of only one specific discipline at a time—often without relating those insights to the underlying scientific principles (Umwelt im Unterricht, 2015).

Apart from the specific climate context, teaching systems thinking in the classroom is not a new endeavor. Even if this is not specifically anchored in the German curricula, various models of a general system competence have been proposed (Mehren et al., 2018; Rieß et al., 2015; Frischknecht-Tobler et al., 2008; Assaf & Orion, 2005; Ossimitz, 2000). Although these models differ in terms of the number of competence levels or areas, they all have in common that there are levels or areas that focus more on basic knowledge about systems and an understanding of system organization, and other levels or areas that are more related to knowledge application and/or system-appropriate intention to act. The model of the Swiss SYSDENE[1] group (Frischknecht-Tobler, Nagel & Seybold, 2008, 27f.), for example, proposes the four Competence Areas (I) "Describe system model", (II) "Grasp dynamics", (III) "Make predictions", and (IV) "Assess action plans" (ibid., p. 30), see Table 1. The Competence Areas I and II together form the competence complex "Reconstruction of System" and areas III and IV form the competence complex "Use of System Model". The existence of these two main competence complexes has been empirically validated by Mehren et al. (2018).

Table 1 *Breakdown of the individual Competence Areas of the SYSDENE model (2008)*

	Competence Areas I-IV according to Frischknecht et al. (2008)	**Description**
Competence Complex 1: **"Reconstruction of System"**	I: Describe system model	This is about clarifying the term system. In the concrete model, the learner identifies the elements of a system and its boundaries. Simple relationships between the system elements are worked out.
	II: Grasp dynamics	The learner now analyzes the quality of the interrelationships in more detail. They recognize and describe effects of compensating and amplifying feedbacks. Temporal changes and delays are also described, e.g. by means of graphs. Linear and non-linear growth is differentiated.
Competence Complex 2: **"Use of System Model"**	III: Make predictions	Based on interactions and dynamics of a system the learner evaluates or even designs different scenarios and discusses predictions.
	IV: Assess action plans	Based on their acquired knowledge, the learner now evaluates concrete measures for system optimization and, if possible, puts them into practice.

Although several authors (Clausen, 2015, Tschekan, 2009, Siebert, 2007) consider a change of setting, authentic encounters, and a combination of different teaching methods essential for

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[1] Acronym for „Systemisches Denken für eine nachhaltige Entwicklung“ which translates as „Systems thinking for a sustainable development“.

teaching complex relationships, only Clausen's studies (Clausen, 2015, Clausen & Christian, 2012) are known to incorporate out-of-school learning environments for building systems literacy in students. Other studies employed simulation software (Mischo & Rieß, 2008; Klieme & Maichle, 1994), hands-on models (Bell, 2004; Komorek, 1997) or physical games (Frischknecht-Tobler et al., 2008) at school. Some approaches at least combined analogue and digital materials (Brockmüller, 2019; Feigenspan & Rayder, 2017; Sommer, 2006; Assaraf & Orion, 2005).

Most of the studies mentioned above followed an experimental design measuring the short-term effects of their instructional interventions by means of a pretest/posttest procedure (Brockmüller, 2019; Bräutigam, 2014; Mischo & Rieß, 2008; Hlawatsch et al., 2005). The following overarching findings for teaching and measuring systems competence can be identified from these studies:

- Systems competence, or systems thinking, breaks down into different skill areas that can be viewed as at least additive components, and possibly as stages that build directly on each other (Mehren et al., 2018; Rieß et al., 2015; Bräutigam et al., 2009; Ossimitz, 2000).
- It is possible to promote systems thinking through teaching (Brockmüller, 2019; Bräutigam, 2014; Mischo & Rieß, 2008; Assaraf & Orion, 2005; Hlawatsch, 2005; Maierhofer, 2001; Ossimitz, 2000). Nevertheless, some studies show that only a certain percentage of students adapts a truly systemic understanding (Sommer, 2005; Bell, 2004; Steinberg, 2001; Kliemle & Maichle, 1991).
- A one-time intervention using only one method seems less effective for building broader systems understanding than a combination of texts, videos, simulations and discussions. (Brockmüller, 2019; Mischo & Rieß, 2008).
- Few studies so far have based their empirical investigations on longer interventions of several months (Bollmann & Zuberbühler 2016; Assaf & Orion, 2005).
- The assessment of skills in the different domains or levels should be analogous to the requirement of these domains. Basic, domain-specific knowledge that falls more into a basal competence area can possibly be determined with a simple knowledge test; higher-level or more complex system competence areas, on the other hand, are more likely to be determined with graphical representations or reasoning patterns (Bollmann-Zuberbühler, 2010, p.27).
- The intervention studies described above have almost exclusively developed and tested domain-unspecific system understanding that is not tied to specific natural systems. Exceptions are Brockmüller 2019 and Assaraf and Orion 2005 (geography) and Clausen 2015 (biology). However, general process-related competencies have limitations, because "without content, competencies can neither be developed nor used" (Stanat, 2018, p. 20).

The diagnosis of systems competence or the measurement of its development was done in almost all studies by means of written tests. These included a combination of multiple-choice questions, argument-counterargument tasks, the transformation of complex problems into flow and effect diagrams, and vice versa, and predicting possible outcomes of different scenarios. Very few of these studies examined changes in system competence using concept maps, interviews, or drawings (Clausen & Christian, 2012; Sommer, 2005; Bell, 2004). However, since the system competence models mentioned above assume a change in complex ideas, it would be helpful to consider theories of conceptual development when asking if and how students learned.

As Wilhelm and Schecker (2018) noted, empirical studies in recent decades have repeatedly revealed inconsistency, contradictions, and instability in student conceptions (ibid., p. 50). This is reflected in diSessa's (2018) heuristic framework, Knowledge in Pieces (hereafter ‘KiP’). According to KiP, there is a profound difference in the knowledge system of a layperson compared to that of an expert. To explain a phenomenon, a layperson draws on loose, intuitive fragments (‘p-prims’) that are only slightly abstracted from everyday experience. An expert, on the other hand, has a stable, differentiated, and domain-specific knowledge system. Achieving this requires that p-prims are incorporated in a meaningful way, which happens reluctantly and often needs support (Amin, Smith & Wiser, 2014). According to diSessa, adequate conceptual understanding only emerges after years of adaptation towards expertise. On the way there, new elements are added to a knowledge system that so far seemed coherent to the learner, which may temporarily lead to increased inconsistency (Hopf & Wilhelm, 2018).

Project Context of the Study

Within the framework of the project a teaching-learning sequence was developed following a Design Based Research (DBR) approach (Figure 1). DBR means that the development has happened in an empirically validated multi-step process (Baumgartner, 2003). The core of this sequence was a systematic linking of the interdisciplinary natural science education of German comprehensive schools with three non-formal learning environments. After a preliminary phase, characterized by an in-depth study of the literature and by the planning of the teaching concept and the research methods, a total of three intervention phases followed.

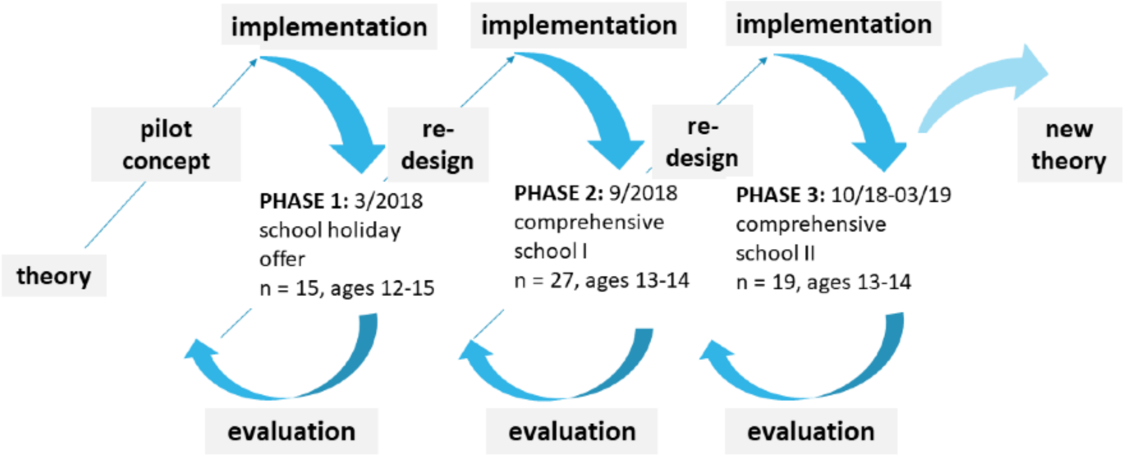


Figure 1 *The three phases of the DBR project*

Phase 1 primarily tested initial learning tools and research methods in the context of a four-day vacation offer for interested young people. From these empirical findings, the didactic means and research methods were adapted, refined and differentiated. In the following Phase 2 they were applied for the first time in the context of interdisciplinary science teaching of a 7th grade at a German comprehensive school. Phase 3 ran as part of the weekly compulsory elective lessons over the school term of 2018/2019 at a different comprehensive school. A total of 17 teaching units took place distributed over three months.

The structure of the sequence was based on the SYSDENE model of System Competence (Figure 2).

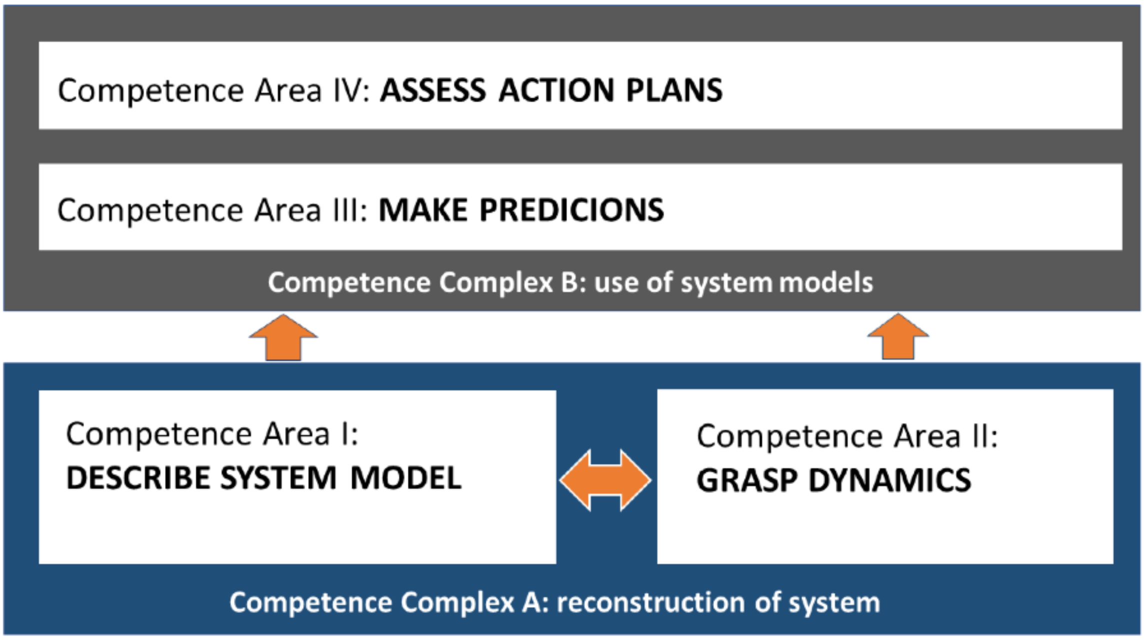


Figure 2 *The SYSDENE Model of System Competence with its four Competence Areas (CA I-IV) by Frischknecht-Tobler, Nagel & Seybold (2008)*

From other models mentioned above, only very limited realistic and achievable skills for 13-year-old students could be derived. For example, Rieß et al.'s model (2015) assumes that at the very basic level, students already master all abstract system-theoretical fundamentals (and therefore terms as „linear"/"nonlinear" and „feedback") and that at the highest level of systems competence they would be able to independently assess the structure, the validity and the predictive uncertainty of different systems models (ibid., p. 18).

The here described teaching-learning sequence was structured by seven questions that build on each other and which the students pursued in the respective places: at school (medium grey) and outside of school (light grey), see Figure 3.

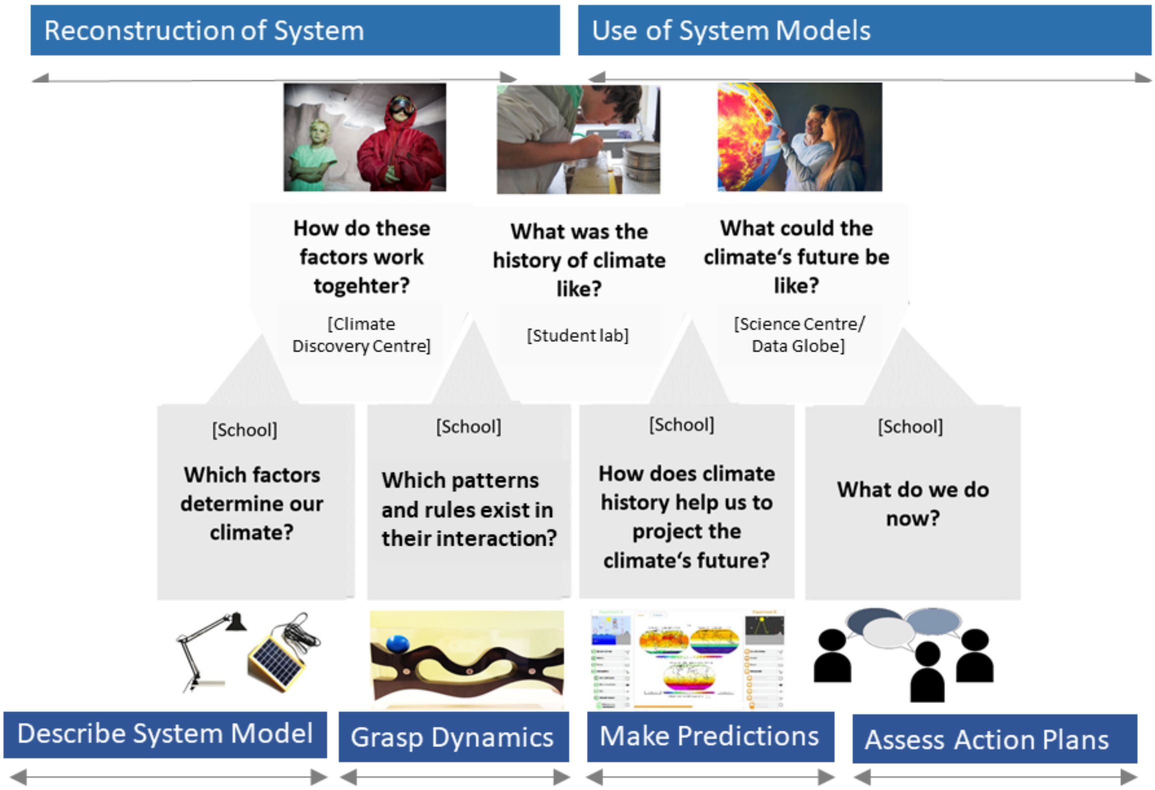


Figure 3 *Teaching-Learning Sequence based on the SYSDENE model. The sequence's aims and contents are explained further in Appendix 1.*

First, the students explored the system elements of climate through experiments at school – exemplified in figure 3 by a model illustrating the angle of incidence of the sun. At the Klimahaus Bremerhaven, a climate discovery center, they then emotionally and physically experienced how these factors interact and form stable climate zones. Back at school, the students used hands-on models to explore the patterns and rules in the interaction of system elements. These include, for example, cycles, chain reactions or, shown in the graphic, tipping points (as for an explanation of the models, see Appendix 1/Day 5). At the MARUM lab at Bremen University, the students then analyzed a drill core sediment to reconstruct climate fluctuations in the Earth's history. Here they also applied first concepts, for example, the significance of tipping points for the climate history of the Earth. With their knowledge of the interaction of system elements and climate fluctuations, the pupils now modeled the climate using the Monash University Interactive Simple Climate Model (https://sci-web46-v01.ocio.monash.edu/mscm/overview_i18n.html?locale=EN). This model simulates the most important physical processes of the climate system in a simplified way. Through virtual experiments, the importance of individual components of the climate system (e.g. ice, oceans, clouds, CO_2) and their interactions can be investigated by learners. The dynamic interaction of climate factors across the Earth and the possible future effects of human intervention could then once again be vividly experienced by the pupils using a 3D animated data globe at the Universum science center Bremen. The final activity was a quiz at school, in which the group that collected the most complex arguments on various statements regarding climate change and mitigation strategies won. Appendix 1 traces the entire sequence planning in the sense of a didactic backward logic (Richter & Komorek, 2019). This planning is oriented towards the subject logic of the contents and focuses on the learning processes that need to take place in order for the students to be able to reconstruct the contents as intended. Appendix 1's color saturation (left column) marks the Competence Areas of the SYSDENE model CA I "Describe system model" (light gray), CA II "Grasp dynamics" (medium gray) and CA III/IV "Make predictions and assess action plans" (dark gray).

Study Objectives and Research Questions

From the literature review, two research desiderata have become apparent. Firstly, no study is known to the author that has been devoted to the development of systemic thinking in the specific context of climate. Secondly, advocates of the Knowledge-in-Pieces theory postulate that large-scale cognitive changes can only be traced if one also looks at details of learning in small time segments (diSessa, 2018; Campbell, 2012). This acquisition process itself has so far largely remained in the dark when it comes to systems thinking development. Therefore, the author aimed this study at deriving a description of cognitive development patterns towards system competence in the special context of the climate.

To answer the main research question "How do the learners' conceptual understanding of climate as a system change throughout the sequence?" a few specific sub-questions were addressed, of which the following three are in the focus of this article:

- Does the 3-month intervention render a change in students' ability to reconstruct the organization and the dynamics of the climate system?
- What patterns in the development of system competence can be traced throughout the sequence?
- To what extent do these developments correspond to the SYSDENE model of system competence?

Methodology

Since the entire study was set in the regular classroom of a comprehensive school and volunteer schools and teachers had to be recruited for the in-depth intervention, this study relied on convenience sampling. All procedures followed were in accordance with the ethical standards of the Lower Saxony State Education Authority, Office for Schools and Education. Informed consent was obtained from all students' parents for the children being included in the study.

The sample of this third DBR phase consisted of 19 seventh grade students of an integrated comprehensive school who had selected "Natural Science" as their first or second desired course. At the integrated comprehensive school, biology, chemistry, and physics are taught integratively in the subject of natural sciences at secondary level I (corresponding to ISCED level 2). The performance spectrum was heterogeneous, as is typical for this school type, with a total of three pupils with special needs and five pupils with language impairments. Overall, there was a strong expression of medium grades, but with quite a high affinity for STEM subjects, see Table 2.

Table 2: Sample of DBR Phase 3

number of students		age (Median)	STEM interest (on 5-point Likert scale)			school performance (estimated by class teacher)		
male	female		mean	min	max	high	medium	low
13	6	13	3.9	2.3	4.8	4	9	6

DBR is considered a methodological framework in which the data collection methods are determined by the context and the development goals, so that "all available data sources and research strategies [are used] that contribute to answering the research question" (Döring & Bortz, 2016, p. 73). Therefore, a mix of methods was adapted for the study in that explorative-qualitative methods were supported by statistical data. Thus, this study should be viewed as an embedded type of mixed-methods research with a focus on qualitative data. In total, three perspectives of the development process, namely 'products', 'processes' and 'reflections', were illuminated and different instruments were used for the data collection for each (see Figure 4).

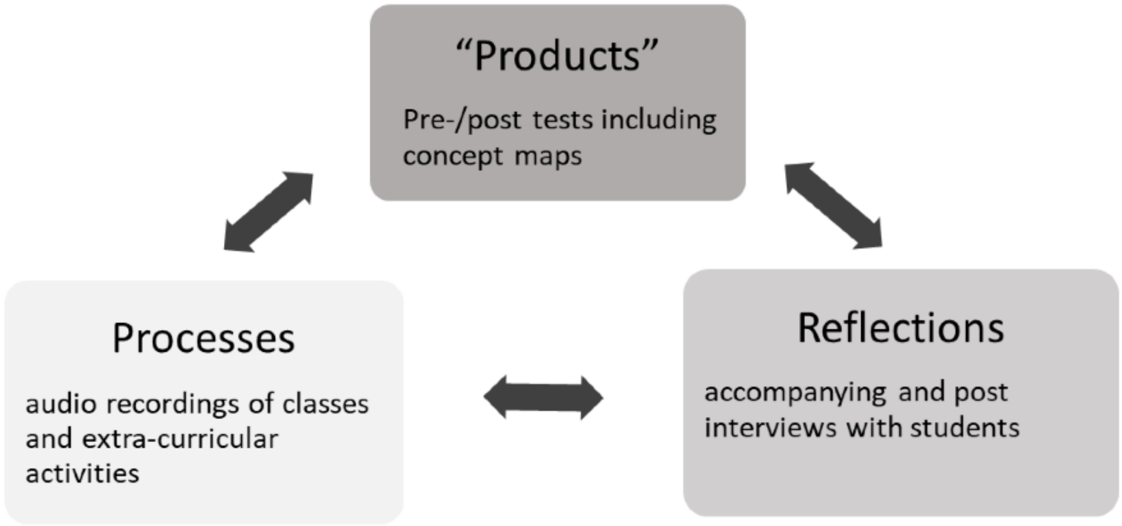


Figure 4 *Three perspectives on the development process and the data collection instruments applied for each*

The performance of the participating students was assessed by a test one week before the implementation of the sequence and one week after its completion. The intervening process was traced with the help of audio recordings of the conversations in the respective learning environments (see Figure 5). As can be seen in Figure 5's blue and dark grey rectangles, the sequence was divided into three thematic phases (I, II, and III/IV) for the data analysis to better anchor the development process over time. These thematic phases were oriented towards the SYSDENE model described in the literature review and in the Project Context of the Study chapter.

To complete the picture by means of reflections, accompanying interviews were conducted with selected students at three points during the sequence. A total of six students were selected: two students with low school performance, two with medium school performance and two students with high school performance. Two students of comparable ability levels were interviewed together in order to create a conversational rather than an interrogative atmosphere.

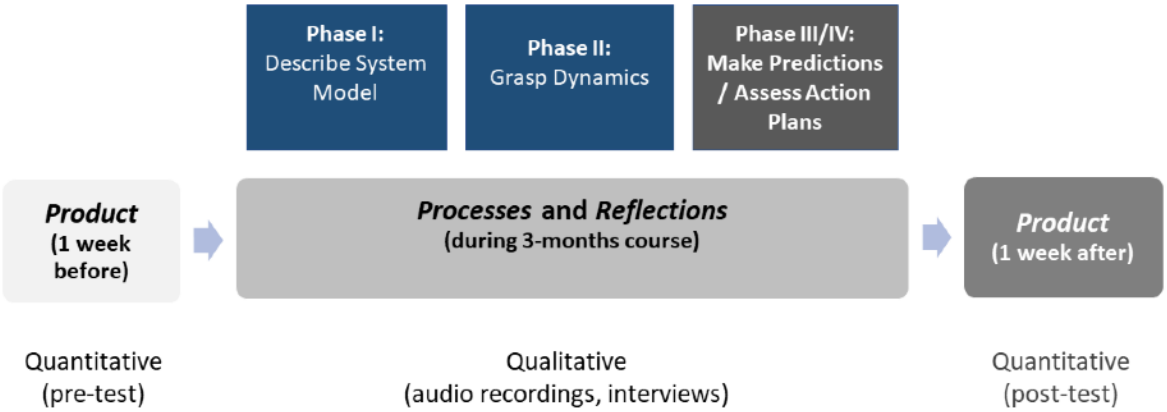


Figure 5 *Data collection in chronological order*

Pre-/post test

For the pre-/post-comparison, a short test was developed that almost exclusively mapped the SYSDENE competence complex "System Reconstruction" and thus the Competence Areas CA I "Describe Models" and CA II "Grasp Dynamics". Existing tests of domain-specific system understanding were judged to be too difficult to use in the field. They would have exceeded the duration of a lesson by far and the seventh graders would have most likely been demotivated. A valid picture of their abilities could thus hardly have been derived in this way. In favor of a manageable test length for the 13-year-old students, modelling and problem-solving skills depicted in the Competence Areas III and IV were solely traced by student interviews and audio recordings of the class discussions. In the unannounced test, only those aspects were evaluated that are relevant to this sequence, so that a clear area-specific understanding of the climate system could be recorded. The test (see Appendix 3) comprised six questions with two to three sub questions each plus a section on demographics and STEM-interest. Altogether this could be completed in less than 45 minutes.

Relating to CA I "Describe Models", the students had to define the term "system" as well as the terms "stable" and "unstable" and apply them to climate and weather. They were also asked to reconstruct the climate system using a concept map with ten given terms that had to be connected in a meaningful way. Other tasks required an understanding of more dynamic interactions in the climate (corresponding to CA II "Grasp Dynamics"). In this section, the students had to explain a supposed contradiction: locally very low temperatures despite global warming. Furthermore, they were confronted with different situations that visualized chain reaction, feedback and tipping point. The students had to predict the outcome of these situations, both in the pre-test based on their prior assumptions and in the post-test based on their experience with the analogue models. In a second step, they were asked to apply each situation to processes in the climate system.

Most of the tasks were open-ended and level-unspecific, thus allowed answers at different levels. The competence level is hence not reflected in the task itself, but in the coding instructions for the task. It was decided to include the judgement of a second, independent rater into the evaluation to increase reliability, which is typically limited for open-ended question tests. For this purpose, a scoring matrix was developed, whose wording was adapted on the basis of joint pilot assessments. Finally, the arithmetic mean was calculated for each test from the assessments of both raters. In order to derive performance differences of the group before and after the sequence, a Wilcoxon signed-rank test for dependent, nonparametric samples was calculated using SPSS software. Since six students missed the last class, the post-test could only be collected from 13 of the 19 pupils. Due to the small sample size the data were not normally distributed, hence the decision to use a nonparametric test.

For analyzing the results of test task 3, the concept map, an evaluation method practiced by Clausen and Christian (2012) was adapted. The authors propose an ordinal scaled scoring system for determining the quality of the statements made on a map. The scoring scheme takes the statements' complexity into account: simple, descriptive statements are scored lower than hierarchical relationships, and these in turn are scored lower than causal relationships. To the resulting total score, the number of system elements mentioned (up to 11) was added. As Appendix 5 shows, the scoring system was adapted to the study's context. For example, system feedback was also accounted for over and above the aspects highlighted by Clausen and Christian (ibid.). Furthermore, in addition to clearly incorrect statements, which scored zero points, partially correct statements were also considered, e.g. if there was a correct causal relationship, but the term was used vaguely due to the students' limited prior knowledge.

Audio Recordings and Interviews

All interviews and audio recordings in class were transcribed using the 2018 to 2020 versions of the MAXQDA software. In order to be able to trace conceptual developments from moment to moment, all transcripts were analyzed employing a content-structuring content analysis according to Kuckartz (2018). Figure 6a shows the process of this type of content analysis, which comprises seven phases – from initiating text work to simpler to more complex analyses of the resulting data material. Characteristic of this procedure are feedbacks and loops, i.e., the development of categories takes place in several top-down and bottom-up steps.

However, research question 1 required not only the identification of topics and argumentation strategies but also an evaluative classification of content; after all, the aim was to depict the *development* of the students' system understanding, which implies a gradual unfolding of understanding and skills. For this purpose, another method after Kuckartz (ibid.) was used, the evaluative content analysis (Figure 6b). Categories were formed on the data material whose characteristics were now ordinal and no longer purely thematic (ibid., p. 123ff.).

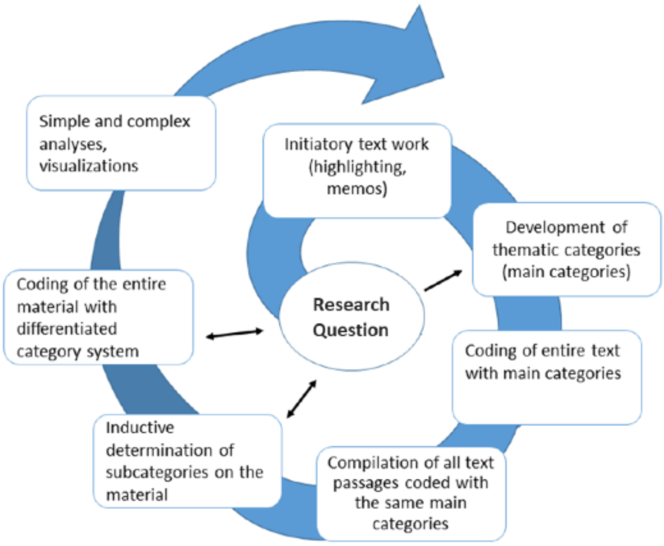


Fig 6a: *Content structuring content analysis according to Kuckartz (2018)*

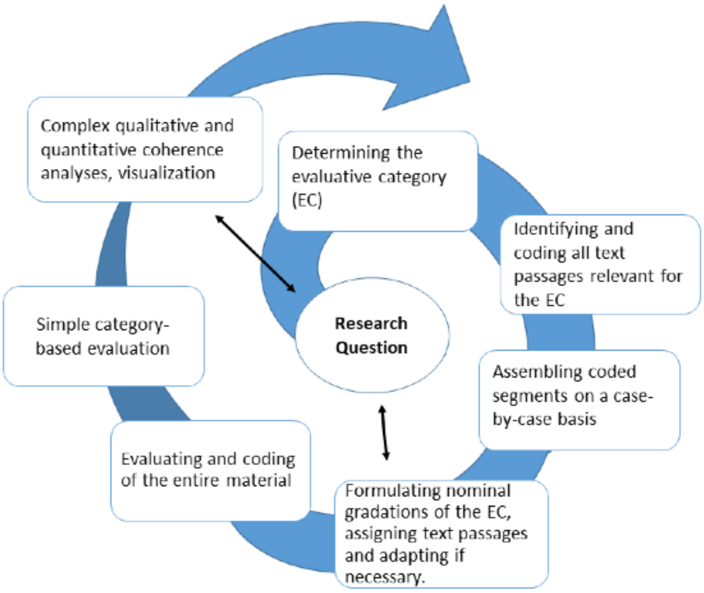


Figure 6b*: Evaluative content analysis according to Kuckartz (2018)*

A comprehensive category guide was developed for all three research questions (Appendix 2). On the one hand, the categories were fed deductively from the research questions and the underlying theories of systems competence, but they were also developed inductively directly from the material and finally applied to all transcripts. This approach resulted in a total of seven thematic categories of climate-specific system understanding, namely. “Description of climate factors”, “Basic scientific concepts”, “Weather/climate distinction”, “Idea of cause-effect”, “Concept of regulation”, “Concept of dynamics”, and “Complexity of Problem Analysis”. All relevant student statements on these seven subject areas were then additionally evaluated using evaluative, four-level codes according to their subject-related meaningfulness. These are referred to as Performance Levels 0, 1, 2, and 3 below (see Figure 7 and Appendix 2).

For the coding process, a second coder was thoroughly familiarized with the research questions, theoretical constructs, and category meanings. In doing so, a procedural approach was taken, which is quite common in qualitative content analyzes and which seeks to minimize non-conformities through discussion. The goal was not to present a quantitative inter-coder agreement, but rather to find consensus in clarifying discussions (ibid, p. 105). For this purpose, the entire system of categories belonging to a particular research question was alternately tested jointly and in parallel on part of the material, before being discussed and then discursively developed further. Only then was the entire body of material completely coded again.

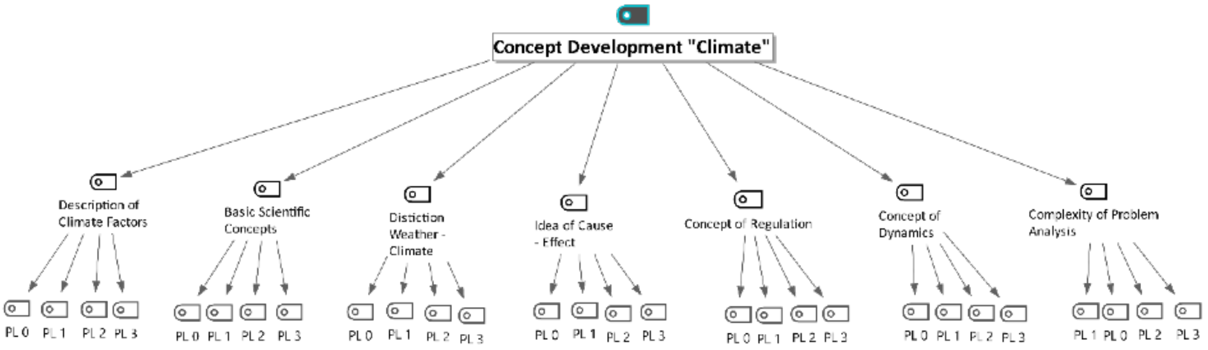
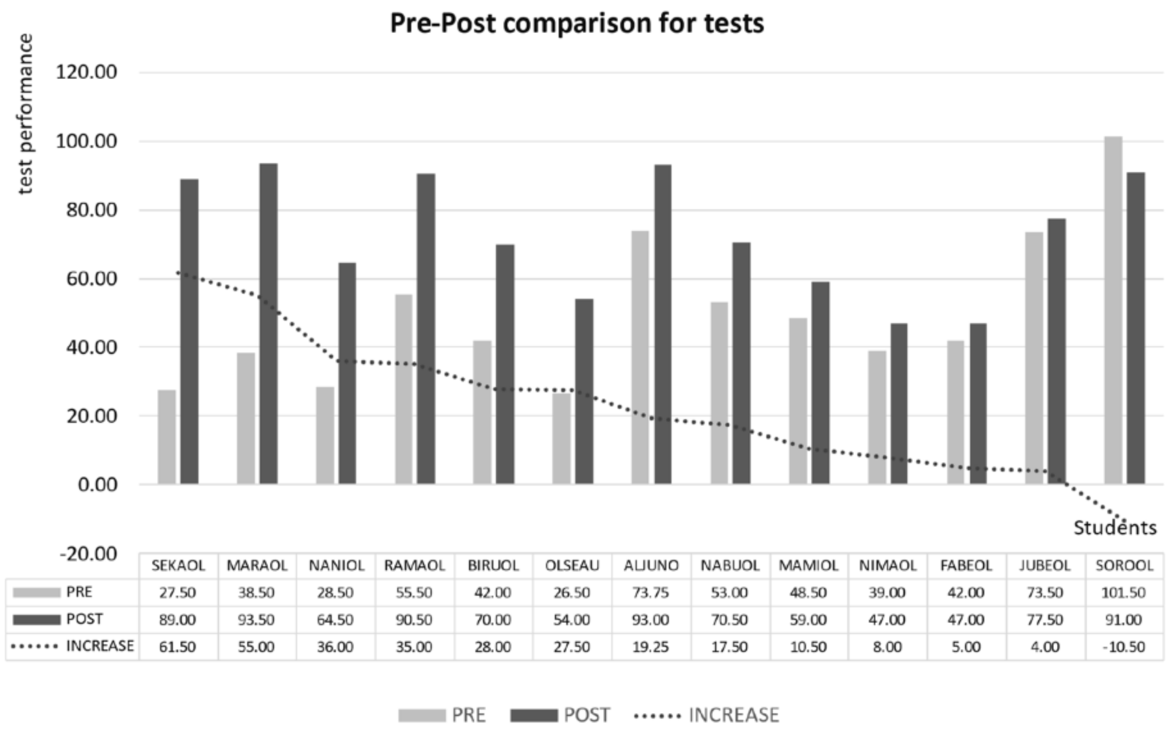


Figure 7: *Seven thematic categories of climate-specific system understanding and their four performance levels*

Results

The graph (Figure 8) ranks the test results by performance gain (dark grey dotted line). A Wilcoxon Signed Rank Test (Figures 9a and b) indicates that the results of the pre-test (Median = 42,0; SD = 21.9) and post-test (Median = 70.5; SD = 17.6) differed significantly and with a strong effect (Wilcoxon-Test: $p = 0.002$, r = -0.901). Thus, three months into the sequence, the group was able to reconstruct the organization and dynamics of the climate system much better than at the beginning.



	SEKAOL	MARAOL	NANIOL	RAMAOL	BIRUOL	OLSEAU	ALIUNO	NABUOL	MAMIOL	NIMAOL	FABEOL	JUBEOL	SOROOL
PRE	27.50	38.50	28.50	55.50	42.00	26.50	73.75	53.00	48.50	39.00	42.00	73.50	101.50
POST	89.00	93.50	64.50	90.50	70.00	54.00	93.00	70.50	59.00	47.00	47.00	77.50	91.00
INCREASE	61.50	55.00	36.00	35.00	28.00	27.50	19.25	17.50	10.50	8.00	5.00	4.00	-10.50

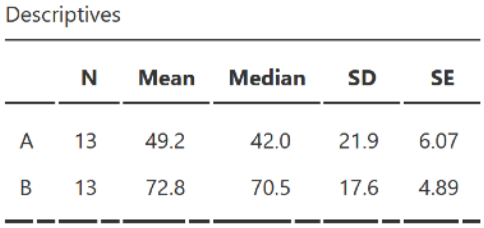
Figure 8: *Test results—Pre-/post comparisons*

Paired Samples T-Test

			Statistic	df	p	Mean difference	SE difference		Effect Size
A	B	Student's t	-4.13	12.0	< .001	-23.6	5.71	Cohen's d	-1.15
		Wilcoxon W	4.50		0.002	-22.8	5.71	Rank biserial correlation	-0.901

Note. H_a $\mu_{\text{Measure 1 - Measure 2}} < 0$

Figure 9a: *Statistical test results*



Descriptives

	N	Mean	Median	SD	SE
A	13	49.2	42.0	21.9	6.07
B	13	72.8	70.5	17.6	4.89

Figure 9b: *Descriptive statistics*

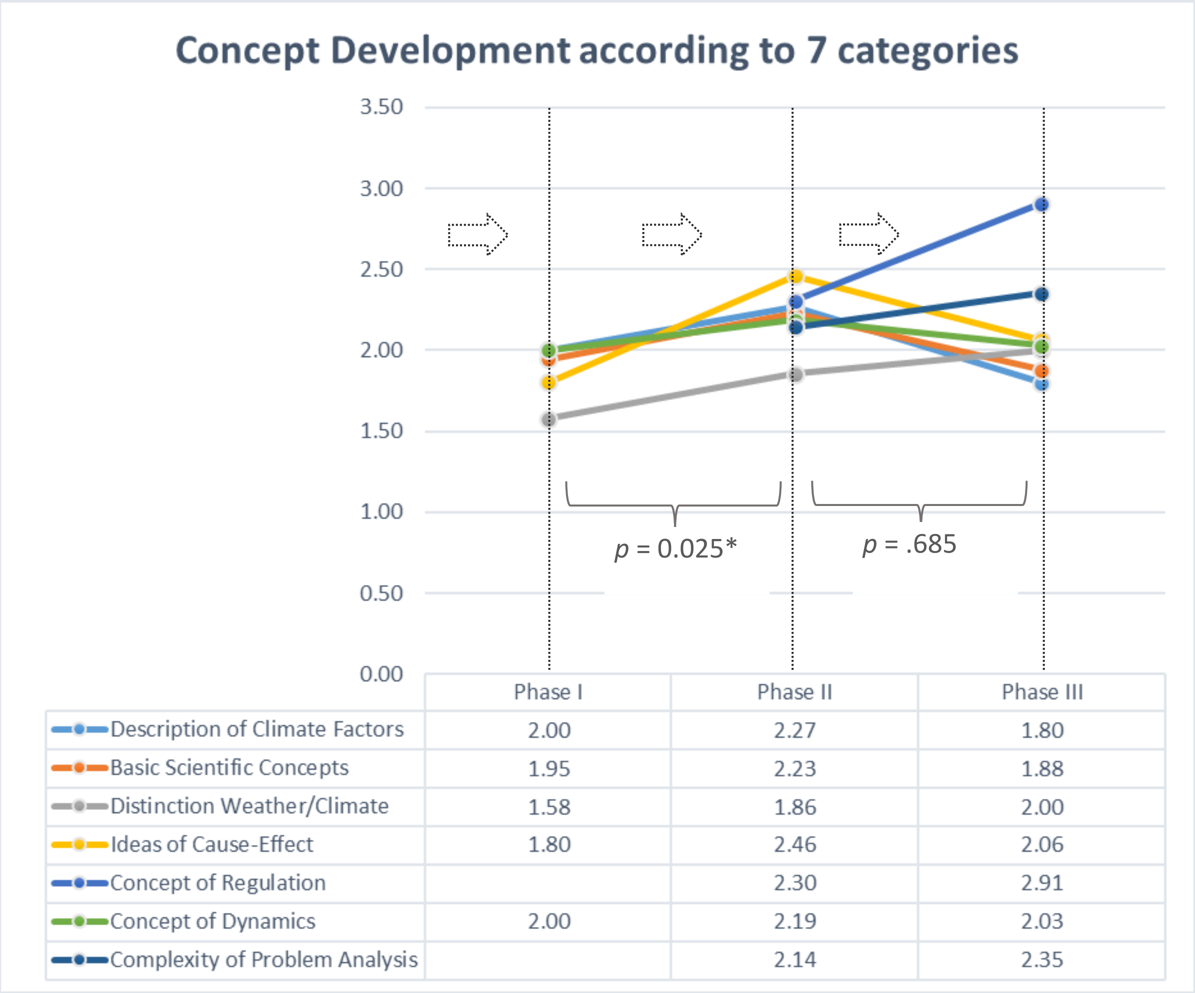
For an evaluative analysis, the entire development process was now broken down into three phases I, II, and III/IV. Each of these time segments roughly corresponds to one Competence Area (CA) of the SYSDENE system competence model. In Appendix 6, CA I "Describe system model" is highlighted in light blue, CA II "Grasp dynamics" in medium blue, and CA III/IV "Make predictions and evaluate action plans" in dark blue. For each of the three phases, all data from the relevant audio recordings and student interviews were included. Direct comparisons between the three phases are limited because not all categories appeared in comparable frequency during all phases (see Appendix 6). Therefore, a qualitive quotient was calculated for each competence category per phase, which considered relations rather than absolute numbers. For this purpose, the student statements per category of a certain level were each multiplied with a performance-related factor 0, 1, 2, or 3:

- Performance Level (PL0), when a learner could not give any explanation at all, was not scored at all in the numerator.
- Statements belonging to level 1 (PL1) were scored once
- statements belonging to level 2 (PL2) were scored twice
- statements belonging to level 3 (PL3) were scored thrice,

which resulted in this formula:

$$(PL0 \bullet 0 + PL1 \bullet 1 + PL2 \bullet 2 + PL3 \bullet 3) \div (PL0 + PL1 + PL2 + PL3).$$

The line diagram (Figure 10) illustrates that two categories of system competence, "Description of climate factors" and "Basic scientific concepts", developed noticeably in phase II compared to phase I, but decreased in their professional quality during phase III. The categories "Ideas of cause-effect" and "Concept of dynamics" also increased in quality during phase II and declined later but remained above the initial value. Only for "Weather/climate distinction", a steady increase over all three phases and for "Concept of regulation" and "Complexity of problem analysis" a strong increase between phases II and III could be noted (these categories did not yet play a role in phase I). A Wilcoxon test showed that when taking *all* categories into account, the total increase between phases I and II is statistically significant ($p = 0.025$) but not the total drop between phases II and III ($p = 0.685$). Still, the decline is relevant for single categories, namely situations in which the students were supposed to recall climate system elements, explain basic scientific concepts or basic cause-affect relations.



	Phase I	Phase II	Phase III
Description of Climate Factors	2.00	2.27	1.80
Basic Scientific Concepts	1.95	2.23	1.88
Distinction Weather/Climate	1.58	1.86	2.00
Ideas of Cause-Effect	1.80	2.46	2.06
Concept of Regulation		2.30	2.91
Concept of Dynamics	2.00	2.19	2.03
Complexity of Problem Analysis		2.14	2.35

Figure 10: *Development of seven competence categories according to quality quotient*

Using qualitative content analysis of the conversations and the student interviews as well as the maps and written answers of the tests, the initially positive development of “Description of climate factors”, “Basic scientific concepts”, and “Ideas of cause-effect” can be well understood. The students were able to relate most of the experiments (e.g. condensation) to weather or to climate (reflection/absorption, angle of incidence of the sun, currents) and to recognize the climate factors in the climate zones at the climate discovery center. One main pre-conception that had initially occurred in all pupils’ minds was that the greenhouse effect damages the atmosphere and that this only happens due to human impact. The students were able to revise both these ideas surprisingly quickly. All ideas expressed by learners in later transcripts had changed from a ‘hole-in-the-atmosphere’ idea to a ‘cage’ idea, i.e. that an increasingly dense atmosphere no longer allows warmth to escape, which is much closer to the scientific idea (see first student quote below). By the end of the sequence, the majority of students also distinguished the natural greenhouse effect from the anthropogenic one. Although cognitively quite demanding, they were also able to reconstruct the connection between climate and the angle of incidence of the sun (quote 2), to explain condensation, to explain the formation of ocean currents (quote 3), and to apply concepts like reflection in different contexts, as quote 4 illustrates.

1) **S1_m:** [...] Earlier the sun passed through the atmosphere, then it hit the earth, then it either went back into space or it hit the earth again from the atmosphere, but now the sun's rays often don't leave the atmosphere, and so the earth warms up. (291118_Interview S2_w + S1_m, position 73)

2) **I:** What about the sun in the polar region? **S2_m:** The sun has a longer way through the atmosphere […] and it heats up a larger area than at the equator. (291118_Interview S1_m + S2_m, position 84)

3) **S2_w:** (...) the blue water was at the bottom because it was cold. And the red one was warm, and that's why it was on top. [...] They mixed and ... um, I think that is how sea currents develop. (140319_PostInterview_S2_w and S5_m, position 231–234)

4) **I:** What would happen if there was no more ice on earth? **S4_m:** Then the earth would heat up more and more, because the white ice can reflect very well. (200319_PostInterview_S4_m, position 92–94)

Looking at the concept maps, one sees this positive development confirmed. In their post-maps, considerably more students successfully used critical climate components that are often not part of pupils' pre-conceptions of climate, such as clouds, land, and ocean currents (cf. Shepardson et al., 2011). A larger number of students also independently brought the terms "reflection" and "evaporation" into play in their post-maps (Table 3). Additionally, students stopped using the vague term "air" and stopped mentioning "pollution". This not only underlines a more differentiated scientific view of climate but also a decline in initial pre-concepts, in this case, that general environmental pollution is a cause of climate change.

Table 3 *Frequencies for single terms, pre- and post-maps comparison.*
Pre-given terms = grey, additionally used terms = white

Term	**Pre**	**Post**	**Change**
Clouds	8	15	*+7*
Land	7	14	*+7*
Ocean currents	7	14	*+7*
Oceans	8	13	*+5*
Climate zones	7	12	*+5*
Humans	10	14	*+4*
Ice/glaciers	11	14	*+3*
Sun	12	15	*+3*
Greenhouse effect	14	14	*no change*
Plants	10	11	*+1*
Atmosphere	13	11	*-2*
Evaporation	2	6	*+4*
Reflection	0	4	*+4*
Growth	0	3	*+3*
Pollution	6	1	*-5*
Air	9	0	*-9*

Despite the initially rapid progress in the field of CA I, uncertainties concerning the basic climate elements and the application of basic scientific concepts reappeared at a later stage. For instance, when they were supposed to repeat the basic climate components for the Monash climate model two months into the sequence, all five addressed students were only able to recall single elements. As for the greenhouse effect, although the pupils had quickly developed a plausible concept, the question as to how the disappearance of the atmosphere would impact the Earth’s climate proved overwhelming in the student interviews, as the following example illustrates.

> **I:** [...] What do you think would happen to the temperatures if we had no atmosphere? // **S5_m:** Yes hot!! Sahara times ten! // **I:** If there was no atmosphere? // **S2_w:** Yes, it would be warm and what else.... uh. // **I:** Why would it be warmer? // **S2_w:** Because uh the sun comes in better, I mean, the sun's rays. And then it all gets warmer. (140319_PostInterview_S2_w+S5_m, pos. 100-105)

Furthermore, in spite of developing a coherent concept for the formation of ocean currents (and despite the phenomenon of wind being explicitly explained several times as an analogy to water currents), some students described trees as the cause of wind by the sequence’s end:

> **I:** What causes wind, S2_w?
> **S2_w:** Eh... oh dear, trees? (140319_PostInterview_S2_w + S5_m, pos. 226)

Competence Area II (system dynamics), was characterized by great heterogeneity right from the beginning. This relates both to the decoding and application of the hands-on models (some laws such as the chain reaction could be derived from the students much more easily) and to the learners themselves: some also succeeded in reconstructing and applying difficult models, while others did not. For example, four students associated the tipping point model (see Appendix 3, marble run) with an earthquake or a change in the Earth's orbit rather than with an abstract metastable state. Five other students, however, actually saw irreversible changes depicted in the model, and three students explicitly mentioned the term tipping point and specified e.g. "The Earth can compensate for small changes, but not for changes that are too big" (JUBEOL). A similar picture becomes evident for the concept maps. Although the dynamics of the climate were taken into account somewhat more in the post-maps (measured by an increased number of feedback descriptions), this only applied to 45% of the students and the other maps still did not show any dynamic ideas of climate.

As for test question 4, three students interestingly addressed overlaps between the analogue models (see Appendix 3). SOROOL and RAMAOL recognized tipping points in both the domino row and the metastable sink and concluded that in both cases irreversible situations occur. And NABUOL realized that both the coupled pendulums and the metastable sink illustrate a compensation. These students clearly showed that they had abstracted from the concrete models.

When looking at CA IV (resp. the qualitative category "Complexity of problem analysis") it became evident that the students generally argued in rather complex ways when it came to system-friendly behavior and technological approaches to climate change. However, even though the students questioned things and weighed up pros and cons, their argumentative constructs were sometimes conceptually imprecise or scientifically flawed. For example, one boy argued that electric cars are not better than diesel-powered vehicles in terms of their carbon footprint because their batteries contain radioactive acids (Post-Interview S21_m+S23_m_210918, position 172).

Discussion

By examining the data material, seven meaningful variables of climate system competence development could be generated. Not all of them have so far been specified in the SYSDENE model. The increased number of variables in relation to the SYSDENE model results mainly from the fact that at first, many technical basics had to be acquired to build a basis for understanding and modelling the climate as a system. Here, the extraordinary importance of CA I for the development of climate system competence became apparent. Being able to describe the main climate system factors is obviously not sufficient as students also need to understand basic scientific concepts related to the climate (greenhouse effect, water cycle, evaporation, reflection, absorption, photosynthesis, etc.). What is more, they must be able to differentiate between weather and climate and must have a basic understanding of the role of statistics and models for climate research. We can conclude that a model of general system competence cannot be applied 1:1 to the specific system of climate. The aspect of specific expertise on a system that is required has already been noted in the literature (Mehren et al., 2018, p.686 ; Feigenspan & Rayder, 2017, p.146).

Regarding the SYSDENE model, CA I should take even more space in the model because according to Frischknecht et al. (2008) this competence area already involves the notion of cause-effect relationships. In the data analysis of this work, the CA I category "Ideas of cause-effect" clearly intersects with the CA II category "Concept of dynamics", since complex and rudimentary dynamic cause-effect relationships such as effect chains, indirect effects, and temporally and spatially shifted effects already appear here.

What is more, as far as CA II is concerned, it seemed to make sense for the analysis of the text material to distinguish between the aspects of dynamics and regulation, because a real understanding of systems cannot only be derived from a knowledge of cycles, feedbacks and non-linear effects (= variable "Concept of Dynamics"), but also from an understanding of the natural laws that govern these processes, namely, that complex natural systems independently strive for stability (= variable "Concept of regulation").

The fact that the students were generally capable of complex argumentation with regards to climate change mitigation was evident in the relatively strong expression of CA III/IV. This may result from the mainly socio-political perspective under which the students had already dealt with the topic of climate at school prior to the sequence. However, it is precisely in the intertwining of CA I and CA IV that the danger lies as some of the pupils' argumentations were conceptually imprecise or scientifically flawed despite appearing rather complex. Such imprecise basic understandings may well be stumbling blocks in the planning of adequate adaptation and mitigation strategies (Shepardson et al., 2011). In addition, they could lead students to simply recite normative ideas instead of independently deriving such argumentation from a solid base of knowledge, which may lead to a decreased feeling of personal relevance and action intention (Gorr, 2014).

Precisely because inconsistencies in fundamental knowledge occur in the later stages, while other domains have already developed, these results speak less for a stage model of System Competence and more for a model of permanently interlocking fields of competence, as already indicated by arrows in the SYSDENE model.

Implications for Cognitive Development Theories

Cognitive and emotional processing and linking do not necessarily mean that the linking is didactically intended or scientifically correct. This becomes visible in the qualitative results, according to which meaningful connections seemingly only prevailed after a longer phase of increasing disorganization, an observation supporting Hopf and Wilhelm (2018). Leaps in the students' argumentations suggested that ad hoc explanations do not necessarily have to be synonymous with internalized and abstracted conceptions. However, they were at least partly constructed spontaneously and contextually. It can thus be assumed that the development of student models towards scientifically accepted conceptions, especially when complex systems are involved, takes a long time, which reinforces the findings of diSessa (2018).

However, in the concept maps, a progressive systematization and reorganization of the original knowledge system could be traced in the sense of a conceptual development. For some students, changes in the priority of concepts, new relationships between concepts, and a replacement of old concepts are observable, which in the sense of the KiP theory already indicates an advanced concept development (ibid.). For other pupils only the first stages of conceptual development are visible: new elements are added, conceptual priorities change, certain concepts are no longer mentioned, and concepts are partly differentiated by naming precise examples. However, there is a lack of establishing new relationships between terms, a general condensation of the conceptual network and a more complex view of mutual influences—in essence, a systemic view. This supports earlier quantitative studies finding that only a certain percentage of students adapted a truly systemic understanding (Sommer, 2005; Bell, 2004; Steinberg, 2001; Kliemle & Maichle, 1991).

Conclusions for theory and teaching – and limitations

A learner with a non-scientific concept will nevertheless experience it as coherent in their everyday life (Amin, Smith & Wiser, 2014). The reason is that she/he will quickly activate p-prims in changing contexts that appear to plausibly explain a phenomenon (diSessa, 2018). It can therefore be assumed that the more small, detached elements are consolidated, the more difficult it becomes for pupils to develop a stable, differentiated and domain-specific knowledge system as they grow older. Thus, it makes particular sense to implement a learning sequence, such as the one presented here, in grade 7 or 8, when fragments and ideas have not yet become consolidated. As the data suggest, it is e.g. not just a matter of explaining to students the interplay of individual climate factors, but learners would also need to be able to access basic scientific concepts such as reflection, absorption, greenhouse effect, evaporation, water cycle etc. and distinguish between climate and weather at this point in their school careers. If these concepts are introduced earlier, learners can draw on them at this point, which helps decrease cognitive load.

However, this alone may not suffice. Structural concepts and explanatory schemes also need to constantly be refreshed in the course of a student's school career. As Bell (2004) states, "abstract schemata are buried again after some time [...] and [...] the students' competence in applying them fades" (ibid., p. 202 f.). For instance, in order to explain complex processes in the climate as a specific system, it may help if students are already somewhat familiar with general systems thinking at this point. Useful ideas in this regard come from Bollmann-Zuberbühler et al. (2010), who developed appropriate system thinking teaching materials for grades 1-9. In support of moving from an exclusively linear way of thinking to a more systemic one, it could also help if teachers employed concept maps instead of mind maps in their lessons as soon as they introduce new topics. This consideration of network-like interrelationships instead of collecting lose factors could certainly be done across disciplines and foster systemic thinking in students early on.

As for cognitive change, it became clear that although some basic concepts such as e.g. that of the greenhouse effect could be changed quickly and sustainably by the students, this was no guarantee for a successful application of these concepts or analogy building to similar concepts. In the situations described above, the children's everyday experiences repeatedly seem to get in the way of the successful application of newly developed cognitive concepts (Amin, Smith & Wiser, 2014). Thus, the students did not generally use p-prims productively until the end of the sequence. This raises the question of what qualities characterize those learners who develop a stronger understanding of systems and what distinguishes them from learners who develop less. This will be examined in more detail in a separate paper.

Concerning the methods for testing systems thinking, it can be deduced that mere pre-/post-tests (Brockmüller, 2019; Bräutigam, 2014; Mischo and Rieß, 2008; Hlawatsch et al., 2005). assess general system understanding at a certain point in time on the basis of already tested task types. However, they cannot assess how fragmented, domain-specific knowledge integrates into coherent concepts and whether these concepts can be fruitfully and consistently applied in changing situations. This study has begun to address this claim through collecting and analyzing qualitative data. Thus, this work can contribute to a more comprehensive understanding of the learning processes that are characteristic of systems competence development in relation to the climate.

The qualitative content analysis of the students' statements proved to be indispensable for understanding how individual categories of system competence developed over time. Through this multi-method analysis, the importance of time as a factor in systems competence development became strongly evident. Looking at the overall post-test results, which were only collected one week after the sequence's end, it seems that the temporal expansion had a consolidating effect on the learners' concept development when considering Competence Areas I and II. Admittedly though, the test results can only be compared to a limited extent with the statements made by the students in the audio recordings. While in the concept maps the students were asked to assemble given elements in a meaningful way, in the class discussion the students were mostly asked rather openly ("Which elements make up our climate?"). In this respect, it is not entirely clear whether the excellent test results are really due to a consolidation effect or rather caused by a different questioning approach. A completely open question (instruction) also tests memory, whereas the concept maps merely test understanding.

Furthermore, this work has not captured possibly delayed cognitive developments. It would be particularly interesting to see whether and how students interpret future school learning content and everyday experiences based on what they have gained during this teaching-learning sequence. How would they integrate new knowledge pieces and experiences in their extended, or even changed, climate system concepts?

A last word to teachers

In 2022, the University of Oldenburg's working group on Physics Education developed a teachers' manual for the here described teaching-learning sequence. The handout will guide teachers through the sequence with supporting materials in terms of subject matter and didactics but will also leave room for personal focus and a teacher's specific subject expertise. Before the handout is available for use, further development will occur on some hands-on-models that proved difficult for students to understand in the sequence or that, due to their components or outer appearance, tended to promote non-intended ideas in students.

Abbreviations

CA I-IV	Competence areas according to the SYSDENE Model of System Competence by Frischknecht-Tobler, Nagel & Seybold (2008)
DBR	Design Based Research
KiP	Knowledge in Pieces theory as suggested by Andrea diSessa (2018)
PL	performance level
p-prims	According to diSessa, these are intuitive fragments that are only slightly abstracted from everyday experience (2018)

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Appendices

Appendix 1: Sequence Planning

UE	***Cognitions*** **Students…**	***Caused by the following actions*** **Students…**	***…intitiated by (actions and media)*** **Teacher…**
Day 1 / Unit I (School)	- reactivate their prior knowledge of climate and reflect on their own conceptual understanding of the climate system	- work on the pre-test and construct a concept map on their own without predefined terms, only with "climate" as the center - then construct a joint concept map on the topic of climate together with the other students, whereby 11 terms are given, which must be used and may be extended	- illustrates the technique of concept mapping by an example and makes the students do a "dry run" to warm up with the method - hands out a test, which also includes a blank sheet with the term "climate" in the center - Encourages students to construct a large concept map together (using a flipchart and a marker) and supports the interaction process. The construction is based on 11 terms that are "parked" next to the concept map and are gradually integrated.
Day 2 / Unit II (School, laboratory)	- work out difference between weather and climate in class - work independently in small groups to identify critical attributes of weather and climate phenomena - Conduct experiments in these steps: (1) formulate one hypothesis each, (2) conduct the respective experiment and observe the physical processes closely, (3) reflect on initial hypothesis in relation to the observation, (4) formulate what process in the weather or climate the phenomenon represents, and (5) put down on paper their own explanation of the phenomenon	- use of a Power Point presentation that allows for "hypothesis-observation-revision" logic - This is done on the basis of seven experiments in five steps with the help of the experiment materials and the worksheets	- uses prepared power point presentation with supporting visual material - provides hands-on activities and worksheets on seven the phenomena: low pressure areas, the greenhouse effect, reflection and absorption, the formation of currents in water, condensation, the heat capacity of water and the dependence of electrical voltage on the angle of incidence of a light source - arranges the experimental materials in such a way that the students have to make their own arrangements - instructs students in advance on handling and safety regulations - accompanies the process, ensures that everything runs smoothly

Day 2 / Unit III (School)	- recapitulate initial assumptions and perceived phenomena with the help of the other students - place the seven phenomena in a clear context with climate factors.	In class, small groups present their initial assumptions, observations, and explanations, and organize all seven observed phenomena into a graphic of the climate system	- provides a large graphic of the climate system with the system elements sun, atmosphere, greenhouse effect, ocean currents, land, biosphere and humans, to which the individual phenomena from the experiments must be attributed - Summarizes results and explanations after they have been first done by the students - discusses states of matter and uses particle model to distinguish between warm and cold water
Day 3 / Unit IV (Klimahaus Bremerhaven)	- explore, perceive sensory and experience climates of different climatic zones of the earth - focus on specific scenes, objects and texts - identify particularly influential climatic factors of a particular zone by referring back to the previous day's experiments - reflect on living conditions in a particular climate and the adaptive behavior of flora and fauna - form the concept of "tipping of the climate" by means of one interactive station each	- explore independently in small groups different climate zones of the earth staged in the climate house - name the climatic factors that are particularly influential in a particular climate zone and match these to yesterday's experiments using the climate system illustration - Select two objects or installations particularly interesting to them in “their” climate zone and capture them in a photo - Collect information about the objects and independently plan the presentation of the climate zone in class - consult the graphs and texts on the "overturning" of the climate of the Sahel a few thousand years ago and draw conclusions from the example to climate in general	- provides worksheets and clarifies uncertainties, organizes the small groups (composition voluntary) - explains schedule, structure of the exhibition and worksheets in advance - supports the small groups in working on the worksheets at certain points of the exhibition
Day 4 / Unit V, School	- reflect on their exhibition experience - consolidate what they have experienced and learned - reflect on what they have experienced with regard to specific questions. - explore the relevance of what they have experienced for anthropogenic climate change	- report as a small group to other students about “their” climate zone with the help of photos and collected information - discuss in class the effects of anthropogenic climate change in these climate zones and its causes	- provides retreat space in the exhibition, which allows undisturbed collaborative work - moderates group presentations and subsequent discussion

Day 5 / Unit VI (School lab)	**Experiment 1: *Domino process*** - recapitulate experience that a single event can set a whole chain of events in motion, form the term "domino process" from the context of the game and work out its physical and systemic conditions **Experiment 2: *Coupled pendulum*** - Conclude that coupled events do not always have to run in only one direction and construct the term "feedback" from the experience with the pendulum. **Experiment 3: *Sand avalanches*** - Conclude that the pile of sand regulates itself without intervention, in that the small avalanches regularly counteract a too steep accumulation. Construct the term "self-regulation" based on this example. **Experiment 4: *Metastable trough*** - Recall the term "metastable" in the context of the trough model and form the term "tipping point"	In each of the experiments described below, students investigate an issue by a) verbalizing and noting assumptions about the effect, b) conducting the experiment, c) verbalizing and noting their observations, d) reflecting on their initial assumptions, and e) if appropriate, making associations with other experiments and phenomena. **Experiment 1: *Domino process*** Students first build simple domino series and then alternate the domino chain by a) inserting stones of very different sizes and b) building the chain in a branched way. **Experiment 2: *Coupled pendulum*** Students use a frame with two hanging pendulums loosely connected by an elastic spring. Students pull one of the pendulums slightly outward and then release it so that it swings in the direction of the other pendulum. Students observe the gradual change in the deflection of the pendulum that is pushed and the effect on the pendulum that is coupled to it. **Experiment 3: *Sand avalanches*** Students have an oblong glass filled with sand and a protractor in front of them. Students insert the glass into the protractor and slowly rotate the glass completely around several times in sequence. They observe the angle formed by the sand as the glass rotates. **Experiment 4: *Metastable trough*** Students are presented a small marble run in a Plexiglas box with shallow and deeper depressions. They carefully place a ball in the upper well, then grasp the box with both hands and gently push it back and forth. They observe the behavior of the ball as they gradually push harder and harder.	Teacher assigns small groups to carry out the experiments, hands out worksheets and explains how to use them. A helper assists at the individual stations by moderating the group discussions, supervising the completion of the worksheets and answering the students' questions.

Day 6 / Unit VII (School)	- recall initial assumptions and perceptions about the four models - independently relate each of the models to a particular system behavior: Chain reaction, feedback (and resulting) self-organization, or tipping point. - draw parallels from these system behaviors to known phenomena in their everyday life (not yet to climate)	One student per small group presents the group's initial assumption to the other classmates, describes the observation made on a model, and finally reads out the conclusion that was noted about this behavior. The small group then expresses everyday examples in which such behavior can be observed. Further everyday examples are collected in class.	- supports the students' memory with a Power Point presentation in which each model is illustrated again by videos and photos. Summarizes students' findings and explanations
Day 7 / Unit VIII (School)	- recall conclusions of the last lesson regarding the terms chain reaction, feedback (and resulting) self-organization, tipping point. - in groups of 2, they independently relate one of these terms to processes in the climate system - are forced to present their own work results in a comprehensible way and to clarify the connection between climate and the respective model. - further elaborate on the concepts of chain reaction, feedback, self-organization and tipping point in the climate context	- work out a concept (cycle, chain reaction or tipping point) on the computer using texts, pictures and videos that specifically touch on the climate - prepare their results for presentation in class - present their research findings to the class using the presentations they created in small groups. Answer questions and discuss them with classmates	- provides computer workstations and data on a server - a short presentation guides each small group through the work assignment - supervises independent work of the students and is available for questions - encourages students to verbalize their findings - Displays the short presentations created by the students for all to see
Day 8 / Unit IX (School)	- work out and reconstruct the climate history of the earth. - define the concept of natural climate change - find out methods for measuring climate fluctuations	- watch excerpts from the documentaries "Climate Makes History" and "Water and Ice" and look for evidence of how climate has changed throughout Earth's history and how it can be studied using ice and sediment cores. - make links between film and the hands-on models *domino process*, *metastable trough* and *sand avalanches*	- organizes the showing of the relevant video clips and encourages students to watch the videos under specific questions. - Moderates subsequent class discussion

Day 9 / Unit X (MARUM lab at Bremen University)	- elaborate critical attributes of climate history and climate research - emotionally empathize with working conditions of a climate scientist - actively explore methods of climate research, including sensory perception, close observation, and categorization of sediment samples based on critical sensory properties - recognize relevance of specific actions in climate research - reflect experiences with climate research - reflect on current experiences against the background of previous knowledge of climate change and reflect on their out-of-school experience	- follow a slide show of a climate researcher about climate history and climate research - talk with the researcher about her experiences - independently prepare sediment samples by sampling a core and washing it - observe samples with the naked eye and under a microscope - make a drawing of the visible properties of the observed sediment - present own observations and interpretations to the group - discuss how current climate change differs from natural historical climate variations	- course is led entirely by the climate scientist and her two lab assistants - climate researcher concludes the session by asking students if there is a difference between historical climate variability and current climate variability
Day 10 / Unit XI (School)	- collectively form the concept "model" by identifying critical attributes of a model car - abstract the attributes of a model - then in turn apply these attributes to a climate model - form solution hypotheses based on their knowledge acquired so far in the sequence and test them	- consider together, using a model car as an example, what distinguishes this model from a real car. - Identify general properties of a model through discussion. - discuss on this basis about what a climate model could be - use a tablet to familiarize themselves with the Monash Climate Model - discuss and practically explore how different climate factors need to be combined in the model to produce a specific climate - form solution hypotheses based on their knowledge acquired in the sequence so far and test them	- uses a Power Point presentation that visually contrasts a model car and a real car. Collects together with students distinguishing attributes in a bullet point list - provides tablets - assists students in accessing the Monash Simple Climate Model website - practices together with students the use of the online functions of the model

Day 11 / Unit XII (Universum Science Center)	- activate concepts of solar radiation angle, heat capacity, current etc. Sharpen these concepts and establish systemic connections between them. - form an idea of dynamic processes in the global climate - form an idea of possible effects of increasing CO2 content in the atmosphere on global average temperatures and land ice cover - work out and become aware of the relevance of their own actions in climate change - formulate and evaluate technological solutions to limit global warming	- follow a demonstration of the animatable data globe - enter into a dialogue with a geologist and use their own knowledge - work on tasks concerning temperature development, global CO2 distribution and ice melt using the data globe as an information resource and climate simulation. Collect notes on the following questions: • Is the temperature rising at the same rate everywhere on Earth? • Where does most CO2 enter the atmosphere and why? • How is CO2 distributed throughout the year? • According to the scenario, which areas, countries or islands will be under water in the future? - search for and describe means of sustainable energy supply and mobility presented by text, video or objects in the technology exhibition - focus on three specific objects, document them photographically and make notes on their energy-saving effect with the help of the accompanying texts	- geologist demonstrates construction. She involves students in the technical handling from the very beginning. - then supports the students with questions to construct the different globes or data sets (angle of incidence of the sun and its shift in the course of the year, the global ocean current system and the heat capacity of the oceans in the global climate system) themselves by bringing in appropriate experiences from the course. She e.g. asks: • What does the yellow belt across the globe represent? • Why does this area fluctuate throughout the year? • Why does the warming of the oceans "lag" two months behind the highest position of the sun? • What do you see here, what are these swirls? • Why are the swirls of different colors? • How do such ocean currents develop? • What do ocean currents do? - explains what a simulation is, using the example of the global average temperature developing in relation to the increasing atmospheric CO2 concentration - points out at certain points what be relevant later for the processing of the research assignments - teacher provides worksheets, clarifies uncertainties, organizes small groups (composition voluntary), supports them at certain points of the exhibition in working on the worksheets

Day 12 / Unit XIII (School)	- recall what they experienced at the science center and formulate their experiences in a way that is understandable to others - work out the term "energy efficiency" together - define the term "efficiency" and distinguish it from "Energy conversion efficiency” - evaluate the energy efficiency of documented objects and mobility solutions encountered at the exhibition - identify energy inefficient everyday problems - recognize global warming as a challenge (likely) to be solved. - form solution hypotheses and formulate solution steps, - recognize relevance of own actions for global warming and discuss possibilities of own intervention	- orally present their work results from the universe to each other in small groups - with reference to the worksheets, jointly compile research results on the term " Energy conversion efficiency” - follow short teacher-centered documentation on energy conversion efficiency and read textbook texts on the subject - use picture cards to identify everyday energy problems, collect possible more energy-efficient alternatives for action and discuss them with other students	- moderates the group presentations. - explains the term "Energy conversion efficiency" by means of graphics - provides a large concept map and a different colored sharpie
Day 13 / Unit XIV (School)	- recapitulate the term "climate system" and elaborate on it in relation to all four areas of competence (describing basic climate factors, explaining the system's dynamics, making climate forecasts and assessing action plans for dealing with climate change)	- play a quiz together: - discuss in a team whether different statements about the climate are true or false and collect arguments for their opinions.	- moderates discussions and point distributions - summarizes findings from the quiz again at the end
Day 14 / Unit XV (School)	- recapitulate the term "climate system" and elaborate on it	- fill out post-tests - class as a whole continues the large concept map from day 1 with a different colored Sharpie and discusses, changes and adds entries	- moderates the continuation of the concept map and encourages the students to clarify their statements and the terms used by asking questions. - summarizes findings that the teaching-learning sequence has tried to convey

Appendix 2: Conceptual development toward a systemic view of the climate: Qualitative category guide

1.1 Description of Climate Factors	**...describes the idea of which elements determine the climate**	
1.1.1 PL1	Neither the major factors of the climate system nor their relationships can be reconstructed.	*L: What does a volcanic eruption have to do with the climate?* *S1_w: ...Um… the smoke is very deadly. (261018_class conversation, pos. 204)*
1.1.2 PL2	Influencing factors of the climate system can be named but may be incomplete or are only constructed with assistance. Basic relationships between factors are constructed superficially.	***L:*** *[…] have we forgotten anything? [climate elements]* ***S1_w:*** *Atmosphere. But I'm not entirely sure it has to do with the atmosphere. When the sun shines… the gases...um...our atmosphere heats up. (261018_ class conversation, pos. 230-231)*
1.1.3 PL3	Major factors of the climate system and their relationships can be reconstructed autonomously and applied to a certain climate zone, e.g. ice, ocean and sun for the polar zone or sun, atmosphere, ocean, plants for the tropical zone.	***I:*** *Can you remember the elements that determine the climate?* ***S1_m:*** *First, there are vulcanoes that emit greenhouse gases. There are also plants and trees that convert CO2 into oxygen. Then there are the oceans with salt water and the glaciers, which unfortunately are currently melting. And there are the people who build factories and pollute the air... Apart from that, there is the atmosphere, the sun and precipitation. (291118_Interview S2_w + S1_m, pos. 24)*
1.2 Basic Scientific Concepts	**...describes the notion of scientific concepts related the climate such as greenhouse effect, reflection, absorption, water cycle, ocean currents etc.**	
1.2.1 PL1	A basic concept relevant to climate and/or weather is not explained coherently; instead, preconceptions become apparent.	***I:*** *What causes wind, S2_w?* ***S2_w:*** *Eh... oh dear, trees? (140319_PostInterview_S2_w + S5_m, pos. 226)*
1.2.2 PL2	A basic concept relevant to climate and/or weather can be explained in a largely coherent manner, but the explanation remains vague and/or is assisted.	***I:*** *And what is the result of having no plants?* ***S2_m:*** *We don't have clean air anymore. Because plants clean the air by means of photosynthesis. (291118_Interview S2_m + S3_m, pos. 69)*
1.2.3 PL3	A basic concept relevant to climate and/or weather can be explained in a technically coherent manner and distinguished from similar terms.	***S1_m:*** *[...] Earlier the sun passed through the atmosphere, then it hit the earth, then it either went back into space or it hit the earth again from the atmosphere, but now the sun's rays often don't leave the atmosphere, and so the earth warms up. (291118_Interview S2_w + S1_m, position 73)*
1.3 Weather/Climate Distinction	**...describes the idea of how weather events and climate are related to each other.**	
1.3.1 PL1	Weather = Climate: Weather is considered to be synonymous with climate. Weather occurrences are not interpreted as part of a long-term climate development.	***L:*** *Do you know examples that show that our climate is changing, S12_m?* ***S12_m:*** *For example in the summer... the sun shines more often and the temperature goes up, that's how you can tell. (261018_ class conversation, pos. 21)*
1.3.2 PL2	Independent, without statistical reference: Weather is not equated with climate, but the idea is still diffuse, e.g. does not include that long-term climate is composed of individual weather data.	***S12_m:*** *Climate is made up by the weather. And um weather is when you already know when that is. (261018_ class conversation, pos. 76)*

1.3.3 PL2	Independent, with statistical reference: There is a clear idea that weather and climate are independent concepts, but that long-term climate is composed of individual weather data averaged over decades	***S20_m:*** *So, climate includes a longer period of time, whereas the weather exists for a day or a couple of weeks […] And the weather can change very quickly, I'd say, but climate is just... [2s pause, S2 thinks], it normally does not change drastically or all of a sudden [...] The climate has already existed for a very long time. (PostInterview_S14_w + S20_m_210918, pos. 83)*
1.4 Ideas of Cause-Effect	**... describes the development from the idea of merely direct cause-effect connections to the development of the idea that one cause can result in multiple consequences, which may well occur at a temporal and spatial distance.**	
1.4.1 PL1	Direct, monocausal: simple idea that one cause in the climate causes only one direct, immediate effect.	***I:*** *What would happen if we there was no ice on earth anymore?* ***S2_w:*** *It would become... even warmer because the ice.... well, it's cold. And so it cools down the Erath a little. (140319_PostInterview_S2_w + S5_m, pos. 52-53)*
1.4.2 PL2	Vaguely multicausal: idea that one cause in the climate can result in several effects, but the relationships cannot be scientifically substantiated.	***S5_m:*** *Wasn't it that the climate change also causes stronger wind? //* ***I:*** *Why would that be? //* ***S5_m:*** *I'm not sure right now but I got that idea because I heard it somewhere before. (140319_PostInterview_S2_w + S5_m, pos. 222)*
1.4.3 PL3	Indirect, multicausal: idea that one cause in the climate can have several direct and indirect effects, which may differ from their cause in strength, be delayed in time and/or happen elsewhere.	***I:*** *What else contributes to a warming climate?* ***S2_m:*** *Well, if the ice surface is gone it cannot reflect the sun light anymore. Um, it's dark and that's why the sun light gets absorbed and it makes the water heat up. Then perhaps the gulf stream stops and causes some other countries become colder because the stream does not supply them anymore with warmth. (200319_PostInterview_S2_m + S3_m, pos. 139-140)*
1.5 Concept of Regulation	**...describes the idea of how and why the climate is regulated**	
1.5.1 PL1	Anthropocentric and without system reference: assumption that climatic processes are being regulated for human survival.	***I:*** *Do you remember roughly what it is [a system]?* ***S24_m:*** *Yes, a system is something like a computer that runs. [...] the trees are there for us to have oxygen, [...] so that we can live here. So, water, atmosphere and sun. Without the sun or something, we would die quickly. (PostInterview S17_m + S24_m_210918, pos. 133)*
1.5.2 PL2	Not anthropocentric, but not completely founded in a natural system: assumption that climatic processes exist independently of humans, but system reference is not established.	***I:*** *How would you explain to someone what it means that the climate organises itself?* ***S19_m:*** *I would tell them that the climate just... cannot be influenced and just always somehow changes. So, it's never entirely stable. (PostInterview_S19_m_200918, pos. 39-40)*
1.5.3 PL3	Autonomous, founded in a natural system: clear conception of the self-regulatory capacity of a complex, natural system, which can, however, be disturbed by excessive human influence.	*I: And what happens in the Arctic with the sun and the ice – normally? What would be the normal climate if the ice didn't melt?* ***S1_m:*** *Um, I think it would always melt a bit, but new ice would always appear, too. [...] there has always been global warming, for thousands of years, but that's been so slow that animals and plants could get used to it. (291118_Interview S2_w + S1_m, pos. 56-57)*
1.6 Concept of Dynamics	**...describes the development from a sequential idea (simple, linear) to thinking in terms of a dynamic network of many elements that influence each other in non-linear ways. This includes an understanding that effects are seldom proportional to their causes.**	
1.6.1 PL1	Linear, static: simple idea of a sequence with a beginning and an end, both temporally and spatially. Elements in climatic processes are not considered in connection with but detached from each other.	***L:*** *What is a system?* ***S7_m****: A sequence? (231118_ class conversation, pos. 126-127)*

1.6.2 PL2	Linear, dynamic: idea of a process in one direction involving several elements that are connected in the sense of a domino effect. Idea that processes always proceed at a steady pace.	***S4_m:*** *And the warmer it gets, the heavier the rain and the stronger the storms! And the stronger the storms, the more rain, destruction! Again and again. (291118_Interview S4_m + S5_m, pos. 76)*
1.6.3 PL3	Cross-linked, dynamic: Idea of a dynamic network of many elements that influence each other in the sense of positive and negative feedbacks; ideas of cycles instead of starting and ending points. Idea of non-linear processes (e.g. exponential growth), which result in limited predictability of a system’s development.	***S3_m:*** *If there are already large masses of water that are exposed and then the sun shines on them, it gets warm even under the ice, and then it all melts away faster, so it accelerates. (170119_Interim interview S2_m + S3_m, pos. 115)*
1.7 Complexity of Problem Analysis	**...describes how complex a person perceives problems or which actions and interventions seem reasonable to them to mitigate climate change.**	
1.7.1 PL1	Simple: assumption that a climate-relevant problem is clearly solvable with one strategy and thus there is no understanding of side effects or the relative insignificance of a measure.	***T:*** *What does sustainability mean?* ***S7_m:*** *I think it also means, um, that we should do more for the environment, I don't know anymore, but that we should ride our bikes more or something. [...] (220218_ class conversation, pos. 25)*
1.7.2 PL2	More complex, but without system reference: it is not assumed that a climate-relevant problem is clearly solvable by only one strategy. There is a vague understanding of side effects, but these are not justified with a complex interaction in the system.	*S8_m: (commenting on the statement "Global warming mainly brings advantages for Germany. For example, we can go swimming earlier and more often".) Well, when it's summer, it's very warm and then the ice melts more and more. And when the ice melts, a lot of water comes and floods everything. (010319_class conversation, pos. 155)*
1.7.3 PL3	Complex, with system reference: conception of interconnected problems that cannot be solved simply by one strategy. This is justified with a complex interaction in natural and/or social systems. Or: Solutions are offered that take complexity into account.	***S5_m:*** *Coal-fired power plants are generally [...] bad, because when you burn coal, carbon dioxide is released into the atmosphere and it makes the atmosphere denser and less sunlight can go out [...]. Nuclear power plants: Um, there are two sides to that. On the one hand, they are a bit better and healthier for the environment, because it's only water vapour. On the other hand, when they break down [...] radioactive rays may escape and poison trees, people, animals; cause them to die. [...] That's what happened in Chernobyl, for example, there was water nearby and it evaporated and all the rain and stuff came even over here to Germany. (140319_PostInterview_S2_w + S5_m, pos. 187)*

Appendix 3: Student Pre-/Post test

Dear student,

With this questionnaire we would like to learn more about you and your views regarding the climate. All questions are open and the answers are anonymous. No one will be able to link the results of the test to you. However, to enable us to relate the results of the questionnaire to the worksheets in the coming days, please provide a code.

Your code: The first two letters of your mother's first name followed by the first two letters of your father's first name (alternatively grandpa or brother) and the first two letters of your place of birth. Here is an example: Mother Maria, father (or grandfather or brother) Michael and place of birth Olbia = MAMIOL

Please fill in your code here:

☐ ☐ ☐ ☐ ☐ ☐

I'm a girl

I'm a boy

I prefer not to say

I am ______ years old.

How much are you interested in the following topics? In each row, mark the value on the scale that best applies to you. Here 1 is "not at all interested" and 5 is "very interested".

	1	2	3	4	5
Natural Science					
Technology					
Animals					
Nature					
Politics and humans					

What are you favourite subjects? Choose three.

Math

German

English

Religion/Ethics

Natural Science

Social Studies

Economy

Art

Music

Sports

Other

____

How do you learn best? Choose all aspects that are important for you.

watch videos and look at pictures

listen to someone speaking

touch, play and experiment

share and discuss experiences

move and be physically active

read information

be on my own and think in piece

think analytically and logically

1. One often hears the word “system”

a) What do you think is the meaning of this word?

b) What ist a climate system?

c) The climate has the property of organising itself. What does this sentence mean? Can you give an example?

2) Sun, plants, ice, atmosphere, oceans, ocean currents, clouds, land, humans, greenhouse effect, climate zones

a) Put these terms into the form of a concept map on the topic of "climate". You have space for this on the next page. Concept map means: draw connections between these terms and use arrows to clarify causes and effects. Please write on the arrows precisely *how* terms are related.

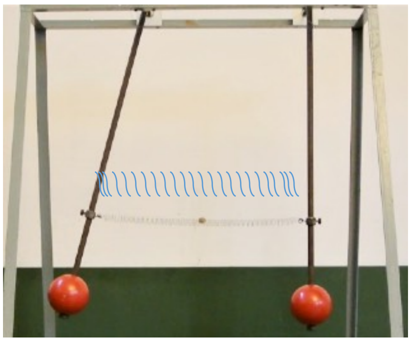
b) Add more words that relate to the climate. Don't forget to relate these to the existing terms in the map.


Climate

3) [No picture rights. For comic strip see https://the-avocado.org/2020/01/25/the-comic-strip-club-sat-1-25-2020/. Last accessed 21 January 2023.]

The guys in the comic are talking about a contradiction: cold temperatures are supposed to occur despite global warming. Do you think this can happen? If so, what could be the reason?

4a) If you were to tip the very smallest stone (on the far right) towards the second stone and let go - what do you think would happen?



4b) Two pendulums are connected by a light spring. What happens if you pull one of the pendulums to the side and let it go?

4c) In front of you is a glass box with a built-in marble run. The ball lies still in a pit.

Imagine pushing the glass box back and forth, first slowly and steadily and then jerkily. What would probably happen?

5) What could the situations 4a, 4b and 4c have to do with the climate?

a) ____

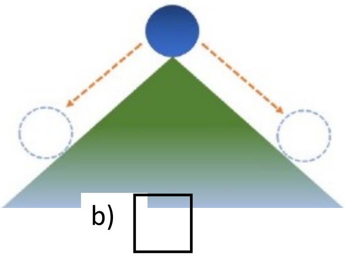
b) ____

c) ____

6) Which of these situations do you associate with the word "stable", which with the word "unstable"? Write an "s" for stable and an "u" for unstable in the boxes below the pictures. Give a brief explanation of your decision below!

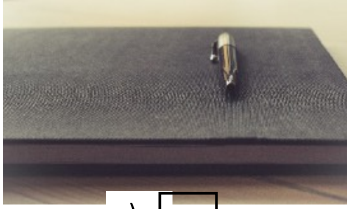
[Adobe Stock 60370106]

a) ☐



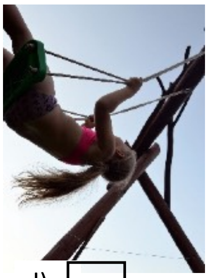
b) ☐

[1249-pxhere.com, creative commons]



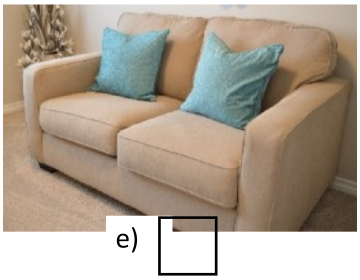
c) ☐

[Wikimedia Commons]



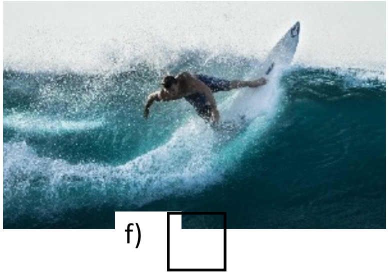
d) ☐

[883269-pxhere.com, creative commons]



e) ☐

[1067819-pxhere.com, creative commons]



f) ☐

6 b) What have the words “stable” und “unstable” to do with climate and weather?

Appendix 4: Interview guide for interim and post-interviews with student groups

Reproduction of the activities of the teaching-learning sequence

- Can you remember the last out-of-school learning environment we went to?
- What was it about there? What were our lessons about?
- Which exhibits / experiments / pictures / videos / conversations do you remember most?
- Was there anything that impressed or surprised you? If so, what do you think was the reason?

Reconstruction of content-related connections between activities

- Which of the things we had discussed before could you use in the Climate Discovery Centre/School lab/ Science Centre and what was completely new for you?
- Was there a connection between what you saw and experienced at the Climate Discovery Centre/School lab/Science Centre and last week's class?
- *How* did we pick up on the experiences in the Climate Discovery Centre/School lab/Science Centre in class?

Note: In the post-interview (interview 3), the last two questions are replaced by:

- What was the dramaturgy of the content of our entire course?
- Can you assign the cards to the learning environments and put them in an appropriate order? [Cards are handed out in no particular order saying “Elements of the climate”, “How the climate system works”, “Climate history”, “Climate models”, “Climate future”, “Mitigate Climate change”, “Climate Discovery Centre”, “School lab”, “Science Centre”.]

Reconstruction of subject-related interconnections

A) Interview 1, end of Phase 1, after visiting the climate discovery center

- What are the elements of the climate, which influences are important?
- How do these influences interact? Can you give examples? [Graphic of the climate model is shown that was already used in class.]
- The Equator (i.e. the Cameroon area) and the Sahel are close to each other, so the solar radiation is quite similar. Why is the climate in Cameroon nevertheless different from that in the Sahel?
- What influences are there in the polar climate and how do they interact?
- If the ice is melting more in the Arctic, how does this influence the climate relationships in the polar zone?
- Did you find it difficult to make connections between the experiments and the climate? What did you recognize, for example?
- In nature, differences usually balance each other out. Can you give a few examples that you explored in the experiment?

B) Interview 2, end of Phase 2, after conducting experiments at school and visiting the School lab

- You recently did experiments at school. Which ones do you remember?
- What did we aim to show with them?
- What do you think is a system? And in what way is our climate a system?
- Which rules of a system became visible in the experiments? [Show pictures of the analogue models]
- What is shown here? Why is there a plus and a minus? [show two graphs comparing negative (stabilizing) feedback processes in the Polar Zone vs. a self-reinforcing process, the ice-albedo feedback]

- Has the climate always been like this in the history of the Earth? Why can the climate sometimes change quite abruptly?
- On the one hand it is said that we are on the way to an ice age, on the other hand we talk about global warming. Can you explain this?
- Did you find it difficult to relate the experiments to the climate? What did you recognize immediately, what was more difficult?

C) Interview 3, end of phase 3, after handling the Monash simple climate model and the data globe

- [Show image of Monash Simple Climate Model] We did something on the computer here. What were we dealing with there?
- What is a climate model and what is it for? What should it include?
- How does knowledge from the past of the climate help us to look into the future?
- What would happen if there was no more ice on Earth? What would happen if we no longer had an atmosphere on Earth?

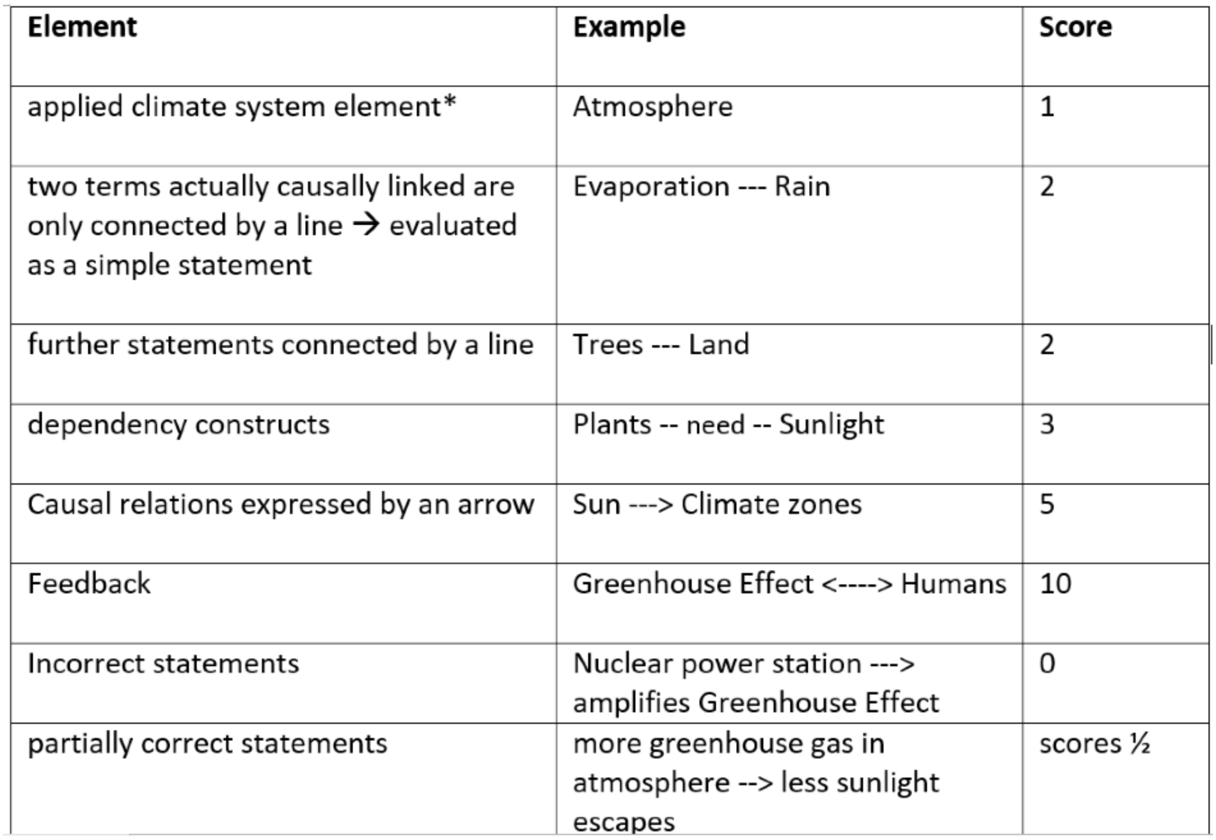
- What do you say to the following statements?

> "We often hear that our harvest is at risk if there is too much drought. But that wouldn't actually be so bad, because we could move cultivation to greenhouses or import fruit/grain."
>
> "Wind turbines are no better for the climate than generating energy from coal."
>
> "When we humans produce CO2, the effect is not necessarily immediately visible or noticeable."
>
> "There's nothing we can do about the greenhouse effect anyway; nature will make up for it on its own."

Evaluation and Motivation

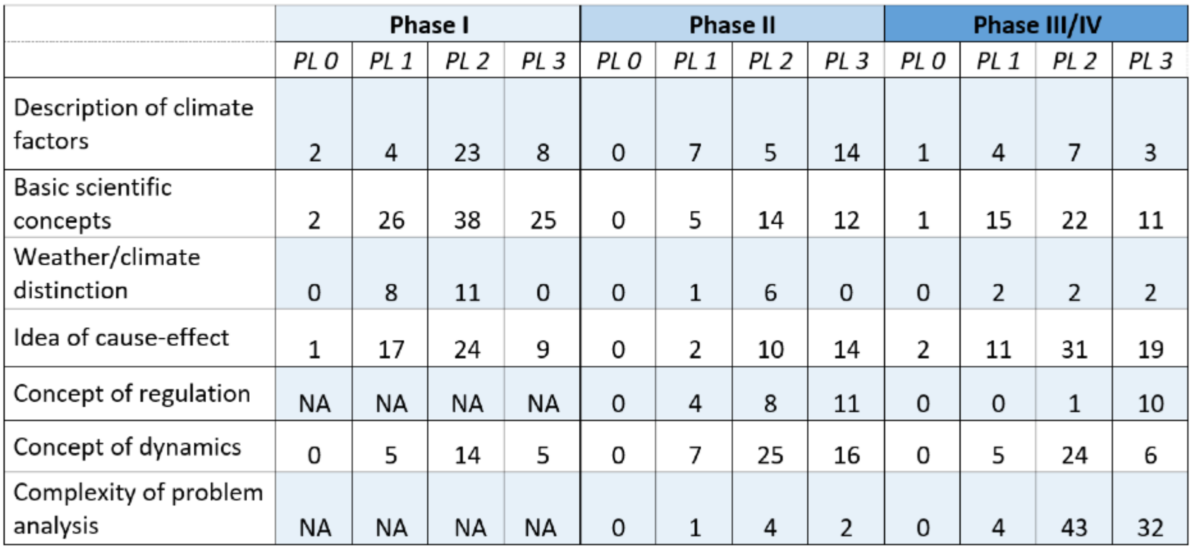
- Did you have the experience of recognizing things / elements during our activities and conversations? How was that? Was it a good feeling or was it rather boring?
- Did our activities in the last weeks / in the course of the whole course contribute to you seeing the climate differently than before?
    - ➔ If yes: What do you see in a different way now? And what was it that changed this view?
- Did you do anything in your free time during the last two weeks as a result of our activities?
    - ➔ If yes: Did you tell anyone about it? Did you google something, read about it, talk to someone about it?
    - ➔ If no: Why not?

Appendix 5: Concept Map Evaluation System adapted from Clausen and Christian (2012)



Element	**Example**	**Score**
applied climate system element*	Atmosphere	1
two terms actually causally linked are only connected by a line → evaluated as a simple statement	Evaporation --- Rain	2
further statements connected by a line	Trees --- Land	2
dependency constructs	Plants -- need -- Sunlight	3
Causal relations expressed by an arrow	Sun ---> Climate zones	5
Feedback	Greenhouse Effect <----> Humans	10
Incorrect statements	Nuclear power station ---> amplifies Greenhouse Effect	0
partially correct statements	more greenhouse gas in atmosphere --> less sunlight escapes	scores ½

Appendix 6: Evaluative codings according to all seven categories across three phases of the sequence. NA = category was not coded



	Phase I				**Phase II**				**Phase III/IV**			
	PL 0	*PL 1*	*PL 2*	*PL 3*	*PL 0*	*PL 1*	*PL 2*	*PL 3*	*PL 0*	*PL 1*	*PL 2*	*PL 3*
Description of climate factors	2	4	23	8	0	7	5	14	1	4	7	3
Basic scientific concepts	2	26	38	25	0	5	14	12	1	15	22	11
Weather/climate distinction	0	8	11	0	0	1	6	0	0	2	2	2
Idea of cause-effect	1	17	24	9	0	2	10	14	2	11	31	19
Concept of regulation	NA	NA	NA	NA	0	4	8	11	0	0	1	10
Concept of dynamics	0	5	14	5	0	7	25	16	0	5	24	6
Complexity of problem analysis	NA	NA	NA	NA	0	1	4	2	0	4	43	32