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How Well Do German A-Level Students Understand the Scientific Underpinnings of Climate Change?

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Abstract: Understanding the scientific underpinnings of climate change is crucial for informed citizenship and future decision-making. This study investigates the understanding of the scientific underpinnings of climate change among German A-level students, focusing on key content areas such as the atmosphere, the greenhouse effect, the carbon cycle, and the distinction between weather and climate. Using a validated climate change concept inventory (CCCI-422), we assessed 501 students from five urban secondary schools in North Rhine-Westphalia. Results indicate that students correctly answered on average 39% of the questions correctly, revealing significant knowledge gaps, particularly in areas like the greenhouse effect and atmospheric composition. We also identified several overarching ideas that many students demonstrate. This study underscores the importance of integrating comprehensive climate science education into national curricula and classroom instruction to foster scientifically literate future generations capable of addressing the global climate crisis.

Keywords: climate change education; misconceptions; climate science literacy; A-level students; greenhouse effect; climate change concept inventory; climate literacy

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1. Introduction

In recent years, the importance of climate change education has become increasingly apparent. As the global climate crisis intensifies [1], it is crucial that young people, especially those at the A-level stage and beyond, possess a robust understanding of the scientific underpinnings of climate change. Grasping these underpinnings is essential not only for informed citizenship, but also for students becoming future climate scientists or policy-makers [2]. Hence, even considering the knowledge–action gap, which indicates that knowledge about climate change does not necessarily influence behavior [3–5], a basic understanding of the scientific underpinnings of climate change is crucial. This understanding helps to empower individuals to make informed decisions [2,6–9] and better evaluate false or contradictory representations of climate change [10–13].

Research indicates that while there is a general awareness of climate change among students [14], there remains a significant gap in their understanding of its scientific underpinnings, showcased by numerous reports on alternative conceptions of the scientific underpinnings of climate change held by learners of different ages, from senior primary school through university, worldwide [14]. Further compounding this issue is the variability in the quality and depth of climate change education [15] across different educational systems. For example, a study by Herman, Feldman, and Vernaza-Hernandez [16] found that the integration of climate science into the curriculum varies widely, with some students receiving comprehensive instruction while others are exposed to only superficial coverage. This disparity can lead to uneven levels of understanding among students.

Although there are many studies on students' understanding of the scientific underpinnings of climate change, a systematic review of the literature demonstrates a lack of quantitative studies assessing students' understanding [14], thus providing a reliable and comprehensive overview for the design of teaching about the scientific underpinnings of climate change. Since A-level graduates include future decision-makers in society, it is interesting to explore the understanding of the scientific underpinnings of climate change that these students hold at the end of their schooling. Additionally, investigating A-level students sheds light on the state of all compulsory schooling.

To address these gaps in our current understanding, this cross-sectional study investigates the understanding of the scientific underpinnings of climate change among $n = 501$ A-level students in the state of North Rhine-Westphalia, Germany, using an extensively validated climate change concept inventory [17], wanting to shed light on the strengths and gaps in students' understanding. Our aim is not to elaborate on effective climate change education strategies [15,18], but to describe the status quo of the understanding of the scientific underpinnings of climate change among current A-level students in Germany.

2. Study Background and Research Context

In this this section, we provide the necessary background for this study by elaborating what we understand as the scientific underpinnings of climate change and reviewing previous studies on students' understanding of these principles.

2.1. Scientific Underpinnings of Climate Change

Climate change is an interdisciplinary topic that can be viewed from different perspectives, and therefore there can never be a single "list" of scientific principles or ideas that are always equally relevant for all views on climate change. However, when it comes to a basic understanding of our climate system and current climate change from a scientific perspective, certain concepts and content areas emerge as essential prerequisites.

Based on the literature [1,19–21] and expert interviews, we [17] argue that there are at least five content areas that should be addressed in science education on climate change. In the following, we provide a translated description of these five content areas provided in Schubatzky et al. [17], explicating what we mean when we write about students' understanding of the scientific underpinnings of climate change. These content descriptions are not intended to describe all the details from a physical perspective but to outline the key content areas.

2.1.1. The Earths' Atmosphere

A basic understanding of the size, structure, and composition of our atmosphere is essential for understanding climate change. It involves understanding that our atmosphere is a thin gas layer whose density decreases rapidly as it rises. It also includes the conceptual division of the atmosphere into different layers, such as the troposphere and stratosphere. However, the atmospheric layers closest to the Earth's surface are the most relevant to weather and climate phenomena because they contain the vast majority of air and because atmospheric warming starts from the ground. It is also crucial to understand that the atmosphere appears to be homogeneous in composition, meaning that there must be enough convection and turbulence to constantly mix gases of different densities.

Additionally, it is important to estimate the proportion of greenhouse gases in the atmosphere, which occur only in trace amounts, and to understand their key property: they are transparent to visible light but interact with infrared radiation.

2.1.2. The Difference between Weather and Climate

One reason why it is important to distinguish between the direct perception of weather and the concept of climate is that personal perceptions of weather can influence our (subconscious) attitudes towards climate change. Studies show that people are more likely to believe in human-caused climate change on particularly warm days than on particularly cold days [22]. Once you have an idea of how our atmosphere, or the air around us, is generally structured, you can ask questions about how the state of the atmosphere or air at a particular place and time can be described. This leads to the concept of "weather". Weather is what we see and feel when we go outside, such as rain, sunshine, cold, or wind.

By measuring certain parameters, such as temperature, the weather can be determined immediately, but not the climate. Climate is understood as something more long-term, which can be described by statistical values such as the average temperature and its fluctuations (variance, extreme values). These differences are not only to be noted on a temporal scale but also on a spatial one; there can be a global climate, but there is no global weather. While it is difficult to predict the weather (e.g., temperature) at a location more than 10 days in advance, climate models can reliably project climate developments (e.g., average global temperatures) for decades.

2.1.3. Climate as a System

To understand climate and its changes, it is not enough to focus solely on the atmosphere. The climate of our Earth must be described as a system in which different components interact. Energy, as well as matter (such as carbon), are exchanged between them. The climate system changes over time under the influence of its own dynamics (so-called feedback effects), natural external influences such as changes in solar radiation (Milankovitch cycles), or anthropogenic influences such as the burning of fossil fuels. Different parts of the climate system react at different speeds to external driving factors. The atmosphere and the near-surface part of the oceans react the fastest. Climate changes occur very slowly in the deep sea, and the large ice sheets react even more slowly to changes. This list of system elements and interactions can be extended almost indefinitely, as the climate system is highly complex, with countless system elements. It has stochastic traits and can be influenced by us but not controlled.

For students, it is important to understand the climate as a system so that they do not expect mono-causal solutions, but rather insist on a cautious (human) approach when intervening in the climate system to avoid unpredictable and irreversible disruptions.

2.1.4. The Greenhouse Effect

Since the current climate change is due to human influences, the greenhouse effect, particularly its anthropogenic component, constitutes another central element of the overall consideration. However, the greenhouse effect is a complex phenomenon that requires several knowledge elements to be linked for understanding. A possible scientific explanation of the greenhouse effect adequate for secondary schools, and which can hence serve as a basis for an appropriate elementarization in education, is as follows:

(Dark) bodies emit energy according to their temperature. This refers to both the amount of energy and the wavelength of the radiation. The Sun predominantly emits visible radiation and is the main energy source for the Earth. The Earth is surrounded by an atmosphere. The greenhouse effect can be illustrated in four steps.

Step 1: About a quarter of the solar radiation is directly reflected into space by the clouds; another quarter is absorbed by the atmosphere. Approximately half of the solar radiation passes through the atmosphere unimpeded to the Earth's surface. Bright areas, such as ice or snow on the Earth's surface, reflect this radiation back into space unchanged.

Step 2: Dark areas such as rocks or oceans absorb the solar radiation and warm up. The dark, warmed Earth's surface emits long-wave thermal radiation due to its temperature. This is a conversion of visible solar radiation into thermal radiation.

Step 3: The atmosphere is only partially transparent to thermal radiation due to trace gases (water vapor, CO_2, etc.). The atmosphere heats from below. This is the natural greenhouse effect on Earth, which raises the average temperature from −18 °C to +15 °C. There is an additional, human-caused greenhouse effect (raising the temperature to +16 °C) due to the increased input of CO_2 in the atmosphere.

Step 4: The warmed atmosphere also emits long-wave thermal radiation—including downward radiation. This further warms the Earth's surface. Ultimately, the Earth emits as much energy as it receives from the sun (radiative equilibrium). As CO_2 levels in the atmosphere increase, more thermal radiation from the Earth's surface is absorbed by the atmosphere. As a result, less energy leaves the Earth (radiative imbalance). On the other hand, as temperatures rise, the ability to emit energy also increases. This leads to a new radiative equilibrium at a higher Earth temperature.

The importance of this concept is evident, especially when considering that laypeople often have difficulty distinguishing between the ozone hole and climate change (e.g., [14]). Thus, news reports about the ozone hole possibly closing by 2050 can cause confusion, potentially leading to the perception of a supposedly decreasing climate change.

2.1.5. The Carbon Cycle

The greenhouse effect can explain why an increase in the concentration of greenhouse gases in the atmosphere leads to a rise in global average temperatures. However, it remains unclear how this enrichment of greenhouse gases in the atmosphere occurs. To understand this enrichment effect, a basic understanding of the so-called carbon cycle is necessary: the knowledge that carbon occurs in different parts or spheres of the climate system and moves particularly between the atmosphere, living organisms, and the hydrosphere (storage–flow scheme), with CO_2 itself being a storage. There is a large amount of carbon that does not participate significantly in this natural exchange. This includes carbon bound in rock form and carbon stored in fossil fuels (solid, liquid, and gaseous) in the Earth's crust.

Without human (or external natural) influences, the exchange of carbon is in a natural equilibrium—just as much carbon flows from the oceans and living organisms into the atmosphere as the oceans and living organisms absorb. This natural equilibrium has kept the CO_2 concentration in the atmosphere relatively constant for centuries. However, burning fossil fuels adds additional CO_2 to the atmosphere, disrupting the natural carbon cycle. Furthermore, deforestation, previously during industrialization and now in the Amazon, results in reduced photosynthesis and slash-and-burn agriculture increases respiration, leading to an increased inflow into the atmospheric storage. During the Carboniferous period, when carbon was stored in fossil fuels, there must have been a natural flow imbalance. Understanding the carbon cycle is thus important for understanding the human contribution to current climate change.

After this description of our understanding of the scientific underpinnings of climate change, we will now briefly review what is already known about students' understanding of the scientific underpinnings of climate change.

2.2. Students' Understanding of the Scientific Underpinnings of Climate Change

In this article, we refer to "understanding" as all thought processes that students may have about the specific content, in this case climate change [23]. Since in this study we are using single-select questions to investigate students' understanding, we cannot differentiate between ad hoc constructions of people or more robust constructs.

Due to climate change being a complex topic, it is not surprising that previous studies demonstrate a rather low understanding of students, showcasing various alternative ideas about the scientific underpinnings of climate change [14]. In line with our understanding of the scientific basics of climate change (see Section 2.1), we will now present a brief literature review of students' understanding and ideas concerning the different content areas constituting the scientific underpinnings of climate change. These descriptions are mainly based on previous review studies concerning climate change education [14,24].

2.2.1. Students' Understanding of the Earth's Atmosphere

Previous studies have revealed various misconceptions about atmospheric composition and anthropogenic changes. For instance, students often overestimate the concentration of greenhouse gases in the atmosphere [7,25], with some even listing CO_2 along with oxygen as a primary component (4). Conversely, there are beliefs that a "normal" or "healthy" atmosphere contains no CO_2 at all [26]. Another common misconception is that greenhouse gases or CO_2 form a distinct layer in the upper atmosphere rather than being evenly distributed [26–28]. Furthermore, the ozone layer is frequently misunderstood and confused with the greenhouse effect [26]. While some students correctly view the ozone layer as a protective shield against UV radiation [27–29], others mistakenly believe that it protects against sunlight [26,27,30].

2.2.2. Students' Understanding of the Difference between Weather and Climate

Many studies highlight that while students generally know that weather refers to short-term atmospheric conditions and climate to long-term patterns [25,31], they often mistakenly believe climate changes can occur within a few weeks (4). Bodzin et al. [25] report that many students confuse weather and climate, and Dawson [28] notes that students often intermingle the terms. However, some students believe that weather and climate are unrelated [32], despite recognizing that climate change can affect weather phenomena. Further misconceptions include weather patterns [28,32,33], extreme weather events [33–37], precipitation, and seasons [33,35,37].

2.2.3. Students' Understanding of Climate as a System

A systematic review showed that fewer studies focus on climate as a system than on the greenhouse effect or the carbon cycle [14]. However, there are still some, where students believe that climate change effects are confined to specific regions, such as the poles [38] or the Northern Hemisphere [25]. There is also a common belief that climate change impacts occur "elsewhere", not where the students themselves live [38,39]. Conversely, some students think climate change effects vary by region, with some believing that the impacts in their part of the world are mostly positive [39]. Feedback effects within the climate system are generally a new concept for many students [7,27], leading to fewer preconceptions. The albedo effect is rarely mentioned by students in the context of climate change [27], and when it is, it is often confused with heat capacity [25]. Furthermore, students struggle with the idea that a small quantity of greenhouse gases can significantly influence the climate [7], believing that any influencing factor must be large. Similarly, students think that variations in the Earth's orbit must be substantial to affect the climate [31].

2.2.4. Students' Understanding of the Greenhouse Effect

Extensive research has explored students' understanding of the greenhouse effect, focusing on the mechanism, greenhouse gases, physical principles, and the distinction between natural and anthropogenic effects [14]. For example, many students incorrectly associate the ozone layer's depletion with an enhanced greenhouse effect, believing a thinner ozone layer allows more heat to enter the atmosphere [7,27,28]. Some also think the Sun is getting hotter or emitting more energy [33,34,40], or that a layer in the atmosphere focuses radiation like a magnifying glass [41]. They often attribute ozone layer destruction to pollution, harmful gases, CO_2, car exhaust, and factory emissions [26–29,40–42]. Additionally, students believe that a specific atmospheric layer traps heat, radiation, or gases, and prevents them from escaping. This layer is often mistakenly identified as the ozone layer, a layer of greenhouse gases, or CO_2 [7,26–28,30]. Some use the analogy of a blanket to explain this trapping effect [7,27,28].

When it comes to greenhouse gases, students often associate greenhouse gases with climate change and global warming [25,28,43]. They describe greenhouse gases as trapping, storing, emitting, reflecting, blocking, or absorbing heat in various ways [7,8,27,28,30,33]. However, many students struggle to identify which gases are greenhouse gases, often incorrectly thinking CO_2 is the only one or not knowing that water vapor is a greenhouse gas [7,25,28,36,44]. They associate increased greenhouse gas emissions with cars, fossil fuel combustion, factories, deforestation, and general human activities [28,33,36,43]. Few students distinguish between natural and anthropogenic greenhouse effects, and students are often unaware that the natural greenhouse effect is essential for life [27,28,43].

2.2.5. Students' Understanding of the Carbon Cycle

There have been some research efforts when it comes to students' understanding of the carbon cycle [14]. This research indicates that students often have a limited understanding of carbon chemistry [7,45], including a restricted awareness of carbon compounds [7] and a tendency to focus on tracking individual carbon atoms in carbon cycle tasks [45]. Additionally, students struggle with the concept of carbon as a building block of living organisms [7]. Students' understanding of the carbon cycle often focuses on atmospheric carbon or CO_2 [7,9,45]. Some students identify CO_2 as the only carbon compound [45] or believe that carbon exists almost exclusively in the atmosphere [7]. When describing the carbon cycle, students often emphasize carbon emissions to the atmosphere [9] and consider oxygen to be part of the carbon cycle [45]. They are frequently unaware of CO_2 solubility and the role of oceans as carbon sinks.

Students often associate CO_2 with destructive properties [8,28,30], and view it as the cause of ozone layer depletion. Some students differentiate between "natural" and "artificial" CO_2, believing that natural CO_2 from respiration can be absorbed by plants, whereas artificial CO_2 from fossil fuel combustion cannot, due to its supposed different structure [26]. Others view all CO_2 as man-made or artificial, believing that a healthy atmosphere contains no CO_2 and that artificial CO_2 causes climate change (29). Furthermore, the human contribution to carbon flows is often overestimated by students [7], while their understanding of human impact on the carbon cycle is generally limited [45]. Students also have difficulties with the principle of mass conservation in the context of the carbon cycle. They may alter the number of atoms [45] or the total amount of carbon on Earth in their representations of carbon flows [7].

To our knowledge, no studies have yet investigated the understanding of A-level students in large cohorts, especially in Germany, leading to our research aim and question.

3. Research Question

The aim of our research is to assess the understanding of the scientific underpinnings of climate change of German A-level students. Therefore, the guiding research question for this article is as follows:

(1) What is German A-level students' understanding of the scientific underpinnings of climate change?

Therefore, we do not only provide an overview of how many questions the students were able to answer, but also provide a content-oriented description of a typical student's conceptions and understanding.

4. Methods

To explore these research questions, we had students complete the climate change concept inventory CCCI-422 [17].

4.1. Sample

The sample under investigation consists of n = 501 A-level students of five A-level-track secondary schools (Gymnasium) in the state of North-Rhine Westphalia in Germany. It is a contingency sample. The schools are all located in an urban setting with school location types 1 and 2 (range 1 to 5), meaning less than state-average migratory background and more than state-average household income. This is in accordance with less than 20% of participants (n = 93) reporting that they speak a language different than German at home with their parents. In summary, the n = 501 students represent the complete A-level graduation classes in their schools. The average age of participants is 17 years (range 15 to 20 years). In our sample there are 238 males, 246 females, 9 diverse, and 8 participants without information.

Of further relevance to the sample is whether their curriculum required the teaching of the scientific principles underlying climate change or not. Although we cannot draw conclusions about what was actually taught, an analysis of the curricula in North Rhine-Westphalia provides some information:

Some of the scientific principles underlying climate change are addressed in the mandatory curricula for lower-level Gymnasium (lower secondary, ages 10–15) in Physics, Chemistry, Biology, and Geography. An analysis of these curricula using search terms such as ‘Atmosphere’, ‘Weather’, ‘Climate’, ‘Greenhouse’, and ‘Carbon’ reveals the following:

- “Atmosphere” is not mentioned.
- “Weather” appears in Physics as an example of systems.
- “Climate” is mentioned in Biology (systems) and Geography (climate zones).
- “Greenhouse effect” is mentioned in Physics and an optional example for a system, mentioned three times in Biology, and in Chemistry as an optional context for man-made effects.
- “Carbon” is covered in Biology (carbon cycle) and Chemistry (atomic structure and carbon cycle).

In summary, the curricula make some optional references to the scientific principles underlying climate change, with Biology addressing the greenhouse effect more than Physics.

For upper-level secondary school (Sekundarstufe II, ages 16–18), which comprises elective courses, the curricula analysis shows the following:

- “Atmosphere” is mentioned in Physics in the context of muons and Sun’s spectral lines.
- “Weather” is not mentioned.
- “Climate” appears in Chemistry (climate projections) and Geography (climate change and adaptation). Biology mentions climate change without specific competence expectations.
- “Greenhouse effect” is mentioned twice in Chemistry.
- “Carbon” is discussed several times in Chemistry with regard to atomic structure and the carbon dioxide–carbonate cycle.

Overall, only the elective Chemistry and Geography curricula for upper secondary cover some of the scientific underpinnings of climate change, often focusing more on the consequences than the underlying science.

Student choices vary, with some receiving years of instruction in these subjects up to the highest class, while others may have dropped them after lower-level secondary school. Data from one school indicate that 84% of students chose Geography, 45% Chemistry, 38% Biology, and 33% Physics, noting that students are required to select at least one natural science subject, with some choosing more than one.

4.2. Design

The study follows a cross-sectional design. The learners were tested once online in situ using LimeSurvey (Version 3.22.4) [46] on their personal device with a test duration of about 20 to 25 min. The students were tested with the help of several university research assistants within one lesson in each school, so there was no interaction possible between students from the same school. Data were obtained two weeks prior to the summer holidays at the end of June 2022. At that time, the A-level exams were about ten months ahead.

4.3. Measures

To investigate the A-level students’ understanding, we used the climate change concept inventory CCCI-422 [17]. It contains 36 single-select items and covers the above-mentioned five content areas: 1. The Atmosphere of our Earth; 2. The Climate as a System; 3. The Carbon Cycle; 4. Climate and Weather; and 5. The Greenhouse Effect. For each item, there is one adequate answer and several alternative answers that are based on previous research about students’ understanding [14], as well as interview studies. It was shown that the CCCI-422 instrument can reliably measure the ability of school students from age 14 years on and university students alike. Furthermore, the CCCI-422 was intensively validated, providing arguments for content validity, construct validity (dimensionality analyses and known-groups validity), and instructional sensitivity.

5. Results

5.1. Descriptive Results for the Sample

A share of 71.8% of the students surveyed believe that current climate change is human-induced, with another 25.5% believing in a mix of human-induced and natural causes, four of the 501 students believing in natural causes only, and nine students being unsure. We also calculated an Intraclass Correlation Coefficient (ICC) to check whether the school level explains a significant amount of variance in student scores. An ICC of 0.06 shows that only about 6% of the variance can be explained by the school level.

5.2. Students' Understanding of the Scientific Underpinnings of Climate Change

On average, students solved 14 of 36 items correctly, that is, 39%. Subsequently, results for each of the 36 items will be reported. For this article, the items were translated into English and the full CCCI-422 questionnaire is available from the authors upon request.

5.2.1. Students' Understanding of Items Related to the Atmosphere of Our Earth

On average, students answered 19% (1.31 points out of 7) correctly, with a standard deviation of 14% (0.95 points). Results for all items regarding the difference between weather and climate are shown in Table 1.

Table 1. Answer distribution regarding items that address the Atmosphere of our Earth. The item stem is in bold, the adequate answer of each item is in italic.

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
A1	**Imagine our atmosphere as though it is a container. Within this container, where do the climate- and weather-relevant processes mainly take place?**		
A1	*The climate- and weather-relevant processes mainly take placein the area closest to the ground.*	*109*	*22%*
A1	The climate- and weather-relevant processes mainly take place in the upper area, the one closest to space.	110	22%
A1	The climate- and weather-relevant processes mainly take place in the middle area, neither closet to the ground nor to space.	247	49%
A1	The climate- and weather-relevant processes take place in all areas in the same way.	35	7%
A2	**The atmosphere of the Earth consists of more than 90% of two constituents. Which two gases are these?**		
A2	*Nitrogen (N_2) and Oxygen (O_2)*	*109*	*22%*
A2	Carbon dioxide (CO_2) and Nitrogen (N_2)	110	22%
A2	Carbon dioxide (CO_2) and Oxygen (O_2)	247	49%
A2	Carbon dioxide (CO_2) and Water Vapour (H_2O)	35	7%
A3	**Greenhouse gases are constituents of the atmosphere that affect the climate. How high is the percentage of greenhouse gases in the atmosphere?**		
A3	*Less than 1%*	*21*	*4%*
A3	Between 1% and 5%	38	8%
A3	Between 5% and 30%	139	28%
A3	Between 30% and 55%	213	43%
A3	More than 55%	90	18%

Table 1. *Cont.*

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
A4	**Which greenhouse gas is the most abundant in the atmosphere?**		
A4	*Water Vapour (H_2O)*	*26*	*5%*
A4	Carbon dioxide (CO_2)	346	69%
A4	Methane (CH_4)	71	14%
A4	Ozone (O_3)	58	12%
A5	**Greenhouse gases are components of the atmosphere that have a particularly strong influence on the climate. What was the proportion of these greenhouse gases in the atmosphere BEFORE INDUSTRIALISATION?**		
A5	*Less than 1%*	*40*	*8%*
A5	Between 1% and 5%	135	27%
A5	Between 5% and 30%	198	40%
A5	Between 30% and 55%	100	20%
A5	More than 55%	26	5%
A6	**Imagine that the proportion of all greenhouse gases remains constant from now on. How would the climate continue to develop?**		
A6	*The climate would continue to warm over the next 50 years.*	*21*	*4%*
A6	The climate would only continue to warm over the next few years.	38	8%
A6	The climate would cool down over the next 50 years.	139	28%
A6	The climate would remain nearly the same as it is today for the next 50 years.	213	43%
A7	**How long on average does carbon dioxide (CO_2) remain in the atmosphere?**		
A7	*About 100 years*	*21*	*4%*
A7	About 2 months	38	8%
A7	About 3 years	139	28%
A7	About 5000 years	213	43%
A7	About 100,000 years	90	18%

Results for Item A1 demonstrate that about half of the students think that climate- and weather-relevant processes mainly take place neither closest to the ground nor to space, while only 22% of students correctly think that most of the processes take place close to the ground.

Results for item A2 indicate that while a good portion of students (22%) correctly identified N_2 and O_2 as the most abundant gases, almost half of the students think that CO_2 and O_2 are the most abundant gases.

Regarding Item A3, Table 1 shows that only 4% correctly named the percentage of greenhouse gases in the atmosphere being less than 1%, while almost two-thirds of the students think that greenhouse gases take up at least 30%. When looking at Item A5, the assumed greenhouse gas percentage before industrialization, the answer distribution only changes to some extent.

Regarding Item A4, about two-thirds (69%) of the students think of CO_2 as the most abundant greenhouse gas, while only 26 students or 5% correctly identified H_2O as the most abundant greenhouse gas.

Item A6 was also shown to be a difficult question for the students, as only 4% identified the correct answer. Most of the students thought that keeping the greenhouse gas levels constant either forces the climate to cool down (28%) or remain the same (43%). When it comes to the timespan CO_2 remains in the atmosphere (Item A7), few students chose the correct answer, while almost half of the students (43%) thought that it remains in the atmosphere for about 5000 years.

5.2.2. Students' Understanding of Items Related to Climate as a System

On average, students answered 54% (4.33 points out of 8) correctly, with a standard deviation of 18% (1.44 points). Results for all items regarding Climate as a System are shown in Table 2.

Table 2. Answer distribution regarding items that address Climate as a System. The item stem is in bold, the adequate answer of each item is in italic.

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
CS1	**When the climate becomes warmer, ice and snow (e.g., glaciers) melt. How do these melting processes affect the climate?**		
CS1	*The climate is quickly getting warmer.*	*283*	*56%*
CS1	The climate is slowly getting warmer.	58	12%
CS1	The climate is getting colder overall.	13	3%
CS1	Melting processes do not affect the climate.	54	11%
CS1	That is not so easy to determine.	94	19%
CS2	**When the climate gets warmer, the oceans warm up. The oceans then absorb less carbon dioxide (CO_2). How does this affect the climate?**		
CS2	*The climate is quickly getting warmer.*	*366*	*73%*
CS2	The climate is slowly getting warmer.	60	12%
CS2	The climate is getting colder overall.	14	3%
CS2	Melting processes do not affect the climate.	22	4%
CS2	That is not so easy to determine.	40	8%
CS3	**When the climate becomes warmer, more clouds form. How does the higher cloud density affect the climate?**		
CS3	*That is not so easy to determine.*	*118*	*24%*
CS3	The climate is slowly getting warmer.	91	18%
CS3	The climate is getting colder overall.	71	14%
CS3	Melting processes do not affect the climate.	86	17%
CS3	*The climate is quickly getting warmer.*	136	27%
CS4	**Imagine that the ice floes on the oceans become fewer in number. What will happen then?**		
CS4	*Less sunlight is reflected from the Earth into space, and the temperature on Earth increases.*	*250*	*50%*
CS4	More sunlight is reflected from the Earth into space, and the temperature on Earth decreases.	16	3%
CS4	More sunlight is reflected from the Earth into space, and the temperature on Earth increases.	161	32%
CS4	Less sunlight is reflected from the Earth into space, and the temperature on Earth decreases.	36	7%

Table 2. *Cont.*

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
CS4	The melting of ice floes in the oceans has no influence on the temperature on Earth.	39	8%
CS5	**Which of the following parts of the Earth influence the climate and weather on Earth?**		
CS5	*The atmosphere, living things, and the oceans*	*397*	*79%*
CS5	The atmosphere and the oceans	32	8%
CS5	The oceans and the living things	29	6%
CS5	Only the atmosphere	6	1%
CS5	Only the people	38	8%
CS6	**What contributes to the distribution of thermal energy on our planet?**		
CS6	*The movement of air and the flow of ocean water, both contribute.*	*415*	*79%*
CS6	Only the movement of air contributes	27	8%
CS6	Only the flow of ocean water contributes	17	6%
CS6	Neither the movement of air nor the flow of ocean water contribute.	43	9%
CS7	**Climate changes have always existed. What distinguishes the current climate change from previous ones?**		
CS7	*The current climate change is progressing more rapidly than before.*	*318*	*63%*
CS7	The current climate change is greater than before.	95	19%
CS7	The current climate change has an impact on humanity.	76	15%
CS7	The current climate change is no different from those observed in previous periods of climate change.	13	3%
CS8	**The different greenhouse gases are present in the atmosphere in varying amounts. The amount of water vapour (H_2O) in the atmosphere is far greater than that of carbon dioxide (CO_2). Despite this, why is carbon dioxide (CO_2) mainly responsible for anthropogenic climate change?**		
CS8	*Carbon dioxide (CO_2) influences the proportion of water vapour (H2O) in the atmosphere.*	*27*	*5%*
CS8	Carbon dioxide (CO_2) accumulates in the upper layers of the atmosphere, and water vapor (H_2O) is more likely to be found near the ground.	108	22%
CS8	Water vapor (H_2O) can be absorbed by plants, while carbon dioxide (CO_2) from fossil fuels does not.	55	11%
CS8	Carbon dioxide (CO_2) is denser than water vapor (H_2O).	58	12%
CS8	Carbon dioxide (CO_2) destroys the ozone layer in the atmosphere, but water vapor (H_2O) does not.	254	51%

When it comes to feedback effects, most of the students could correctly identify simple feedback mechanisms (Item CS1, 56%; Item CS2, 73%; and Item CS4, 50%).

Most students are also aware that various spheres affect the climate and weather on Earth (Item CS5, 79%) and that thermal energy is transported by air and the flow of ocean water (79%).

As shown in Item CS 7, almost two-thirds of the students (63%) share the idea that current climate change is progressing more rapidly than before.

When it comes to more complicated feedback effects in the climate system, such as the positive feedback between CO_2 levels and water vapor levels in the atmosphere, only 5%

of the students chose the correct answer. Most students chose the answer that CO_2 is destroying the ozone hole.

5.2.3. Students' Understanding of Items Related to the Carbon Cycle

On average, students answered 43% (2.56 points out of 6) correctly, with a standard deviation of 23% (1.39 points). Results for all items regarding the Carbon Cycle are shown in Table 3.

Table 3. Answer distribution regarding items that address Carbon Cycle. The item stem is in bold, the adequate answer of each item is in italic.

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
CC1	**Carbon (C) exists in different forms, such as coal, oil, or carbon dioxide (CO_2). How has the total amount of carbon (C) on Earth and in its atmosphere changed over the last 150 years?**		
CC1	*The total amount of carbon (C) has remained the same.*	*58*	*12%*
CC1	The total amount of carbon (C) has increased slightly.	92	18%
CC1	The total amount of carbon (C) has increased greatly.	302	60%
CC1	The total amount of carbon (C) has reduced somewhat.	26	5%
CC1	The total amount of carbon (C) has reduced greatly.	24	5%
CC2	**When fossil fuels are burned, the carbon (C) from these fuels enters our atmosphere as carbon dioxide (CO_2). Can this carbon (C) from the carbon dioxide (CO_2) be absorbed by plants at some point?**		
CC2	*Yes, plants can absorb carbon (C) from carbon dioxide (CO_2) via photosynthesis.*	*289*	*58%*
CC2	Yes, when it rains, the carbon (C) in the form of carbon dioxide (CO_2) enters the soil and is absorbed there by plants.	71	14%
CC2	No, carbon dioxide (CO_2) and the plants do not come into contact because the gaseous carbon dioxide (CO_2) rises up through the atmosphere.	65	13%
CC2	No, the carbon (C) from the combustion of fossil fuels is artificially produced and cannot be absorbed by plants.	77	15%
CC3	**Is carbon (C) found in ocean water?**		
CC3	*Yes, because carbon dioxide (CO_2) can be absorbed by the oceans.*	*294*	*59%*
CC3	No, because oceans are only made of water.	31	6%
CC3	Yes, because water molecules contain carbon (C).	113	23%
CC3	No, because liquids cannot contain carbon dioxide (CO_2).	64	13%
CC4	**Carbon (C) is stored on our Earth in the oceans, living things (plants and animals), areas covered by ice and the atmosphere. In which of these is the most carbon (C) contained?**		
CC4	*In the oceans (and seas)*	*83*	*17%*
CC4	In the living things (plants and animals)	87	17%
CC4	In the areas covered by ice (Greenland, Arctic and Antarctic)	84	17%
CC4	In the atmosphere (air)	248	50%
CC5	**Processes such as photosynthesis and cellular respiration enable carbon (C) to be exchanged between the atmosphere and plants. Which process best describes how this exchange occurred before anthropogenic climate change?**		
CC5	*The exchange of carbon (C) between the atmosphere and plants was roughly balanced.*	*40*	*39%*
CC5	The carbon (C) accumulated in the atmosphere.	230	46%
CC5	The carbon (C) accumulated in the plants.	56	11%

Table 3. *Cont.*

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
CC5	Carbon (C) exchange has only taken place since the current period of climate change began.	23	5%
CC6	**Imagine that starting today the oceans do no longer absorb carbon dioxide (CO_2) from the atmosphere. What would happen?**		
CC6	*The CO_2 content in the atmosphere would increase more strongly than it has up until now.*	*370*	*74%*
CC6	The CO_2 content in the atmosphere would continue to increase, as it has up until now.	55	11%
CC6	The CO_2 content in the atmosphere would remain the same.	31	6%
CC6	The CO_2 content in the atmosphere would become lower, unlike up until now.	46	9%

Regarding the amount of carbon in the climate system (Item CC1), most students (60%) think that the total amount of carbon has increased greatly over the last 150 years, while only 12% chose the correct answer.

Regarding Item CC2 (Item CC2), results demonstrate that over half of the students chose that plants can absorb carbon.

While 59% of the students correctly chose that carbon can be found in ocean water (Item CC3), only 17% could identify the oceans as the biggest carbon reservoir (Item CC4).

Regarding exchange processes between different carbon reservoirs, 39% of students chose that, before our current climate change, carbon exchange between the atmosphere and plants was roughly balanced (Item CC5) and almost two-thirds (74%) correctly identified that the CO_2 content in the atmosphere would increase more strongly if the oceans stop absorbing CO_2 (Item CC6).

5.2.4. Students' Understanding of Items Related to the Difference between Weather and Climate

On average, students answered 58% (4.04 points out of 7) correctly, with a standard deviation of 22% (1.51 points). The results for all items regarding the Difference between Weather and Climate are shown in Table 4.

Table 4. Answer distribution regarding items that address Climate and Weather. The item stem is in bold, the adequate answer of each item is in italic.

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
CW1	**Meteorologists make claims about what the weather will be like in the future. For what maximum period are there reliable weather forecasts?**		
CW1	*For a few days and up to a week.*	*337*	*67%*
CW1	For up to three weeks.	91	18%
CW1	For up to three months.	34	7%
CW1	For up to several years.	40	8%
CW2	**What is climate?**		
CW2	*Climate refers to weather patterns over a longer period of time.*	*307*	*61%*
CW2	Climate is the weather or the weather conditions in a specific place.	129	26%
CW2	Climate is just another name for weather.	22	4%
CW2	Climate is what we notice when we go outside.	44	9%

Table 4. *Cont.*

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
CW3	**For which time period do meteorologists usually make statements about the climate?**		
CW3	*For approx. 30 years*	*137*	*27%*
CW3	For approx. 1 week	161	32%
CW3	For approx. 3 months	92	18%
CW3	For approx. 3 years	112	22%
CW4	**What is the relationship between weather and climate?**		
CW4	*Climate refers to the weather that is observed over a longer period of time. Climate, therefore, represents an average of the weather conditions.*	*343*	*68%*
CW4	Weather and climate describe two different models. There is no correlation between these.	35	7%
CW4	Weather and climate describe weather phenomena at a location. The two terms describe the same thing.	39	8%
CW4	The weather causes the climate. But the climate does not cause the weather.	85	17%
CW5	**Climate change has different effects on our Earth. What are these effects?**		
CW5	*Extreme weather events occur more frequently. The average temperature increases.*	*427*	*85%*
CW5	Extreme weather events occur more frequently. The average temperature remains constant.	26	8%
CW5	Extreme weather events do not occur more frequently. The average temperature increases.	29	6%
CW5	Extreme weather events occur with equal frequency. The average temperature remains constant.	6	1%
CW6	**The Earth's climate regularly alternates between warm periods and ice ages. What is the average temperature difference between the temperature during the last ice age and today?**		
CW6	*4 °C to 5 °C*	*164*	*33%*
CW6	1.5 °C to 2 °C	104	21%
CW6	20 °C to 30 °C	185	37%
CW6	40 °C to 50 °C	49	10%
CW7	**When virtually no rain falls over a longer period of time in summer and thus less water is available than needed, this is called a dry summer. How are the three dry summers that have occurred in Germany (2018, 2019, 2020) related to climate change?**		
CW7	*Droughts would occur even without climate change. Due to climate change, droughts occur more frequently and are more extreme.*	*315*	*63%*
CW7	Droughts are clearly a consequence of climate change. Droughts are caused by climate change.	131	26%
CW7	Droughts are clearly not a consequence of climate change. Droughts would occur even without climate change.	26	5%
CW7	Droughts would occur even without climate change. Climate change will result in less frequent and weaker droughts.	30	6%

Regarding the definitions of climate and weather, about two-thirds of the students correctly identified the forecasting time period for weather (Item CW1), but only 27% of the students correctly identified the time period where statements about the climate are made (Item CW3).

With respect to the difference between climate and weather, results show that around two-thirds of the students are aware of the difference (Item CW2 and item CW4), and hence a third are not.

Regarding consequences of climate change, the majority of students chose the answer that climate change causes extreme weather events (85%, item CW5) and dry summers (63%, Item CW6).

5.2.5. Students' Understanding of Items Related to the Greenhouse Effect

On average, students answered 25% (1.98 points out of 8) correctly, with a standard deviation of 15% (1.21 points). The results for all items regarding the Greenhouse Effect are shown in Table 5.

Table 5. Answer distribution regarding items that address Greenhouse Effect. The item stem is in bold, the adequate answer of each item is in italic.

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
GE1	**Which statement best describes the greenhouse effect on Earth?**		
GE1	*Solar radiation passes through the atmosphere and warms the ground. Thermal radiation emitted by the Earth is absorbed by the greenhouse gases in our atmosphere. The thermal radiation is then transmitted back towards the Earth, as well as in other directions. This causes the Earth to warm up even more.*	*93*	*19%*
GE1	Solar radiation passes through the atmosphere and warms the ground. The ground reflects this solar radiation. This radiation is reflected back to Earth by the greenhouse gases in our atmosphere. This causes the Earth to warm up even more.	159	32%
GE1	Greenhouse gases damage the ozone layer in our atmosphere. In doing so, they create and enlarge the hole in the ozone layer. The ozone hole allows more solar radiation to reach the Earth's surface. This causes the Earth to warm up even more.	148	30%
GE1	Greenhouse gases in our atmosphere concentrate the incoming sunlight. The concentrated sunlight causes the Earth to warm up even more.	38	8%
GE1	Greenhouse gases provide good insulation due to their dense concentrations. Greenhouse gases rise to the furthest extent of the atmosphere, reducing the heat exchange between the Earth and space. This causes the Earth to warm up even more.	64	13%
GE2	**The Sun transmits energy to the Earth through various forms of radiation. In what form does most energy reach the Earth?**		
GE2	*In the form of visible light.*	*36*	*7%*
GE2	In the form of thermal radiation.	114	23%
GE2	In the form of UV radiation.	330	66%
GE2	In the form of radioactive radiation.	22	4%
GE3	**How do greenhouse gases in our atmosphere react with incoming visible sunlight?**		
GE3	*They do not react with visible sunlight.*	*82*	*16%*
GE3	They reflect the visible sunlight.	190	38%
GE3	They absorb the visible sunlight.	62	12%
GE3	They bind the visible sunlight.	48	10%
GE3	They focus visible sunlight.	120	24%
GE4	**Part of the visible radiation from the Sun is reflected from the Earth's surface towards space. How do greenhouse gases in our atmosphere react with this reflected visible radiation from the Sun?**		

Table 5. *Cont.*

Item Code	Item/Answer	Number of Respondents	Percentage of Respondents
GE4	*They do not react with visible radiation from the Sun.*	*74*	*15%*
GE4	They reflect the visible radiation from the Sun.	237	47%
GE4	They absorb the visible radiation from the Sun.	110	22%
GE4	They bind the visible radiation from the Sun.	81	16%
GE5	**The Earth emits thermal radiation. How do greenhouse gases in our atmosphere react with this thermal radiation?**		
GE5	*They absorb the thermal radiation emitted by the Earth and emit it again.*	*134*	*27%*
GE5	They reflect the thermal radiation emitted by the Earth.	222	44%
GE5	They bind the thermal radiation emitted by the Earth.	96	19%
GE5	They do not react with the thermal radiation emitted by the Earth.	50	10%
GE6	**How strong is the average temperature increase of the Earth due to the natural greenhouse effect as compared to the anthropogenic greenhouse effect?**		
GE6	*The average temperature increases due to the natural greenhouse effect is higher than that caused by the anthropogenic greenhouse effect.*	*95*	*19%*
GE6	There is no natural greenhouse effect.	38	8%
GE6	The average temperature increase due to the natural greenhouse effect is lower than that caused by the anthropogenic greenhouse effect.	303	60%
GE6	The average temperature increase caused by the natural greenhouse effect is about the same as that caused by the anthropogenic greenhouse effect.	66	13%
GE7	**Different surfaces can reflect different amounts of visible sunlight. Which surface reflects the most sunlight?**		
GE7	*Snow*	*219*	*44%*
GE7	Oceans	238	48%
GE7	Farmland	21	4%
GE7	Green spaces	24	5%
GE8	**What is the current increase in the average temperature of the Earth due to the anthropogenic greenhouse effect?**		
GE8	*1 °C–2 °C*	*262*	*52%*
GE8	0 °C	6	1%
GE8	2 °C–10 °C	184	37%
GE8	Above 10 °C	50	10%

Regarding a global explanation of the greenhouse effect (Item GE1), 19% of the students identified the correct answer, while 32% chose a reflection-based answer and 30% chose an ozone-hole-based answer. Furthermore, answers regarding item GE2 show that most of the students think that energy from the Sun reaches the Earth mostly in the form of UV radiation (66%) instead of visible light (7%).

When it comes to the characteristics of greenhouse gases, only few students think that greenhouse gases do not react with visible sunlight, which either directly comes from the sun (16%, Item GE3), or indirectly as reflected visible light from the Earth's surface (15%, Item GE4). A share of 44% of students also think that greenhouse gases reflect thermal radiation (44%, Item GE5) instead of absorbing and re-emitting it (27%).

Furthermore, the majority of students think that the temperature increase of the natural greenhouse effect is lower than that caused by humans (60%, Item GE6), while only 19% correctly chose the opposite answer.

6. Discussion

Our overall research question was "What is German A-level students' understanding of the scientific underpinnings of climate change?" The results demonstrated that the investigated German A-level students in the state of North Rhine-Westphalia answered less than half of the items correctly (on average, 14 out of 36 items, or 39%), which can be seen as a rather low understanding of the scientific underpinnings of climate change. Questions regarding the Earths' atmosphere (on average 19% correct) and the greenhouse effect (on average 25%) were particularly difficult for the students of the sample. It can therefore be concluded that there has been little teaching of the scientific underpinnings of climate change, or at least that such teaching efforts have not been very effective.

Questions regarding the content area Climate and Weather were rather easy compared to the other content areas of this investigation, but they were still difficult for the students: about one-third of the students investigated apparently confuse the two notions climate and weather, see, e.g., item CW4. This confusion of climate and weather is also reported in the literature [25,28,47].

When it comes to "The Climate as a System", of note is that the CCCI-422 only asks for simple ideas of systems with simple feedback loops, such as in item KS1, which asks what happens to the Earth's temperature when glacial areas melt (correct answer: it gets warmer faster). In this study, items regarding "The Climate as a System" turned out to be the easiest. However, we think that this is more likely due to the type of questions we asked the students, since previous research has demonstrated very well that system thinking is difficult for students [48].

By interpretating the results of the individual items, several "overarching ideas" emerged that encompassed the results of several ideas. These overarching ideas were determined by discursive agreement among all four researchers involved against the research background on students' understanding of the scientific underpinnings of climate change [14]. The interpretation of these overarching ideas sheds additional light on prevalent misconceptions about the scientific underpinnings of climate change held by the students in the study.

1. The first overarching idea can be summarized as "overestimation of CO_2". This overarching idea can be traced back to items A2, A3, A7, and A4. In item A2, 49% of students incorrectly answered that the air consists mainly of CO_2 and O_2. Items A3 and A7 similarly asked about the percentage of greenhouse gases in the atmosphere now and before industrialization. We reported that more than 60% of the students think that the percentage of GHGs in the Earth's atmosphere now is 30% or more, and 25% of the students think it was more than 30% before industrialization. This implies that students often think the percentage of GHGs in the atmosphere has increased by well over double digits in the last 150 years. The last item, A4, asked which GHG is the most abundant in the atmosphere (H_2O, CO_2, CH_4, or O_3), with 69% of students choosing CO_2, while water vapor is the correct answer.
   Therefore, in accordance with previous research [7,49], we infer that an overestimation of CO_2 in the atmosphere needs to be addressed in climate change education, as today's A-level students demonstrate a low understanding. This misconception is significant because it involves a logical fallacy: students may fail to recognize that although GHGs make up a small fraction of the atmosphere, their impact on climate is significant.
   Future climate change education should emphasize that greenhouse gases (especially CO_2) are only a small part of our atmosphere but have a disproportionately large impact on our climate. This highlights the sensitivity of the atmosphere to even small anthropogenic changes. It is crucial to teach that the Earth's climate system is highly

sensitive to changes in GHG concentrations. Small variations can lead to significant climatic shifts due to the complex interactions within the climate system.
Furthermore, it is noteworthy that the majority of students think that if greenhouse gas emissions were stopped immediately, the Earth's climate would either remain the same or begin cooling immediately. This belief overlooks the persistence of existing GHGs in the atmosphere and the delayed response of the climate system. The idea that small changes can have a large impact should be further elaborated, explaining that the climate system can be influenced by seemingly minor alterations in GHG concentrations, leading to significant and potentially long-term changes. This will help students understand the true nature of the climate system's sensitivity and the importance of mitigating anthropogenic impacts.

2. The second overarching idea we identified can be summarized as "Reflection as the main process of the greenhouse effect" and can be traced back to items GE1, GE3, GE4, and GE5. In item GE1, which asked which statement best describes the greenhouse effect on Earth, 32% of students chose that reflection causes the greenhouse effect on Earth. In item GE3, asking how greenhouse gases interact with incoming visible solar radiation, 38% of students chose that greenhouse gases reflect incoming visible solar radiation. In item GE4, 47% of students think that greenhouse gases reflect visible solar radiation once reflected from Earth. Finally, in item GE5, 44% of students chose that GHGs reflect the Earth's thermal radiation. Previous research has even demonstrated that students who show this type of overarching idea have a more coherent but alternative idea of the greenhouse effect compared to an adequate understanding of the greenhouse effect [50]. Thereby, Reinfried and Tempelmann [41] found that secondary school students' preconceptions significantly influence their learning paths. They identified three preconception types: "isolated pieces of knowledge", "reduced heat output", and "increasing heat input". The latter group, which we think includes students that rely on reflection as the main process of the greenhouse effect, struggled the most to reconstruct their mental models.
3. We summarize the third overarching idea as "Focusing on Ozone and UV". This idea can be traced back to items A4, CS8, and GE1. In item A4 12% of students chose ozone to be the most abundant GHG in the atmosphere. In item CS8, 51% of students chose that CO_2 destroys the ozone layer, and in GE1, 30% of students think that the hole in the ozone layer causes the extra greenhouse effect. Previous research has shown that students demonstrating an ozone-based conception of the greenhouse effect have very fragmented, incoherent ideas about the principles underlying the greenhouse effect [50], indicating that many of the A-level students have a rather fragmented understanding. This is also showcased by the fact that in CS8, over half of the students chose an ozone-based answer, but in GE1, only 30% chose an ozone-based answer. It seems like the ozone-hole seems to be some sort of fallback idea, when students do not have a plausible alternative explanation. Hence, in CS8, which is a very difficult item, students chose the ozone hole explanation, as it seems to be the best ad hoc answer.
4. The fourth and last overarching idea can be summarized as "Confusion about C and CO_2" and can be traced back to items CC1, CC4, and, to some degree, CC5. In item CC1, asking how the total amount of carbon on Earth and in the atmosphere (e.g., coal, oil, or CO_2) has changed over the last 150 years, 60% of the students chose "the total amount of carbon has gotten much larger". In item CC4, asking which part of Earth (ocean, living beings, atmosphere, or glaciers) contains the most carbon, 50% of students chose "atmosphere". And in item CC5, asking how balanced the exchange of carbon between atmosphere and plants was before human-induced climate change, 46%, surprisingly, chose that carbon had already at that time accumulated in the atmosphere. We interpret the students' performance with respect to these items as a "Confusion about C and CO_2", possibly meaning the two are the same or somehow not discernible. This implies that climate change education should focus on explicating these differences, and matches findings from the literature reporting that students

have difficulties tracing the carbon atoms in different molecules and different worldly objects like plants or rock [45], neglecting the cyclic nature of carbon (atoms) on Earth.

In terms of implications, these results demonstrating a rather low understanding are of special importance when we turn to existing deliberate efforts to undermine the science of climate change [10,51]. Effective teaching about the scientific underpinnings of climate change could thereby "inoculate" students against climate change misinformation [13] by making them understand why common myths (or misconceptions) about climate change are false [11]. Hence, the results of our study may very well serve as a sound base for misconception-based teaching revolving around the scientific underpinnings of climate change [11]. For example, people holding the conception "Overestimation of CO_2" may easily be fooled when climate change deniers perpetrate the myth that so little CO_2 in the atmosphere cannot make the difference [52]. Furthermore, an underdeveloped understanding of climate as a system seems problematic because it may lead to unwise actions in case people fall for simple, direct, mono-causal solutions, whereas climate is a complex, non-linear system that can be influenced by humans, but not steered [53].

Additionally, our study is in line with previous research [14], indicating that students' understanding of the consequences of climate change is higher than the understanding of the causes of climate change. A few CCCI-422 items address such consequences, e.g., CW6 reported above, which is the easiest item of the inventory overall, or CW8 "drought summers in Germany". The students under investigation generally did well on these. Overall, it looks like these A-level students had no significant schooling on the conceptual understanding of the scientific underpinnings, meaning the underlying physical causes, of climate change.

As a research implication, it may be worthwhile to take a closer look at what is being taught in current curricula. We would like to show this by example. Mandatory physics instruction in optics at the lower secondary school level often prescribes the teaching of reflection and refraction using visible light. Perhaps the prevalent overarching idea "Reflection as main process of the green-house effect" is a product of such optics instruction, because based on their previous instruction, students do not have at hand other types of radiation (infrared or UV), or forms of interaction of radiation of any kind with matter, as suggested, e.g., in [54]. Possibly fitting into this picture is the fact that 60% of the students surveyed chose UV as the form of radiation in which the Sun radiates the most energy on Earth, confirming a mixing of different types of radiation involved (e.g., [55]). At present, it is unclear where the students under investigation obtained their knowledge, although there are some hints in the literature [14]. So, a deeper look into the actual classroom or into non-formal education may be worthwhile.

7. Limitations

First, we would like to acknowledge that our list of scientific underpinnings of climate change is not exhaustive. Furthermore, it was the aim of this study to describe the understanding of current A-level students. As a limitation, these A-level students' understanding of the meaning of the climate crisis—for life on Earth, for their life, and for life circumstances as we know it—was not investigated. Also left out are the reasons for and possible solutions to the climate crisis. The CCCI-422 used for this study neither covers the urgency of the climate crisis nor the meaning of the climate crisis when climate scientists believe that an atmospheric concentration of 350 ppm signifies the last safe CO_2 level [56].

We have presented four overarching ideas, which were derived by consensus among the authors of this article. It is possible that other researchers would identify other and/or more overarching ideas.

As with any multiple-choice test, it cannot be ruled out that students spontaneously chose instead of showing longer-lasting conceptions, if applicable. Deliberate incorrect choices can also not be ruled out. However, when we tested personally in situ, we observed careful, quiet answering in all courses at all schools, and there were only a handful of trial attempts, usually a few seconds after working time started. It is also possible that, due to the MC design, misconceptions were impressed on the students, which they would not hold freely. On the other hand, it is the MC design that enables mass testing of over 500 students at one point in time. We opted for this design to be able to generate generalizable results concerning A-level students' understanding of climate change.

The CCCI-422 instrument [17] does not examine the construct of confidence with each item, which could potentially shed some light on the difference between lack of knowledge and misconceptions. Another limitation concerns the sample, which may not be representative of the entire state of North Rhine-Westphalia. The sample comes from an urban environment, which is typical for this state, but it does not cover rural areas. However, from our point of view, there is no strong argument why the understanding should systematically be different at different schools.

Zeitgeist can play a role in empirical social studies, and this study was conducted in the period of the EU's Green Deal and the actions of Friday for Future and the Last Generation; however, we believe that zeitgeist would alter beliefs and motivation more than understanding.

Another possible limitation is the mixing of questions addressing whole concepts and questions addressing only one fact (e.g., in the concept area "The atmosphere of our Earth"). For example, factual knowledge about the proportion of greenhouse gases in the atmosphere could be representative of the misleading idea that a large effect (such as the effects of climate change) must always be due to a large cause (high proportion of greenhouse gases in the atmosphere).

8. Conclusions

This study provides a comprehensive analysis of the understanding of the scientific underpinnings of climate change among German A-level students. The findings reveal significant knowledge gaps, particularly in areas such as the greenhouse effect, atmospheric composition, and the carbon cycle. Despite a general awareness of climate change, the depth of understanding necessary for informed decision-making and critical evaluation of climate-related information seems lacking.

The results underscore the urgent need for enhanced climate education that addresses these misconceptions and builds a robust foundation of climate literacy. In conclusion, it is crucial to address the identified misconceptions and improve the overall quality of climate education. This will not only improve students' scientific literacy, but also empower them to become informed citizens capable of making evidence-based decisions to combat climate change. The findings of this study serve as a call to action for educators, policy-makers, and researchers to collaboratively work towards more climate change education that is tailored to students' conceptions in schools.

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